RENEWABLE ENERGY
– prospects for implementation

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This collection first published 1993

The journal *Energy Policy* is published by
Butterworth-Heinemann
Linacre House
Jordan Hill
Oxford OX2 8DP
United Kingdom

ISBN: 91 8811672-7

Typeset by MC Typeset Ltd, Rochester, Kent, UK
Printed by Henry Ling Ltd, at the Dorset Press, Dorchester, Dorset, UK

Preface

Three recent international, political developments have contributed considerably to a revived interest in renewable energy technologies: the UN Conference on Environment and Development, the adoption of Agenda 21, and the formulation of the UN Framework Convention on Climate Change. This new interest in renewable energy focuses particularly on questions of implementation and on trying to understand why so little has happened on a global scale, despite the general interest and despite several local success stories, both in industrialized and in developing countries.

Seen in the context of long-term environmental sustainability, the importance of renewable energy can scarcely be underestimated. 60% of greenhouse warming is estimated to arise from energy-conversion activities, primarily those associated with the combustion of fossil fuels. In this context, there is a premium on non-fossil sources of energy, and in particular on the renewable energy technologies.

These technologies have come a long way in the last decade, and in some cases are economically competitive with traditional fossil fuel supplies. Nevertheless, implementation has been slow, and numerous obstacles appear to stand in the way of a more widespread application of these diverse technologies.

In recognition of the importance of the renewables and their potential contribution to an environmentally sustainable energy system, the Stockholm Environment Institute (SEI) has initiated a number of activities aimed at disseminating technical and economic knowledge about renewable energy technologies. In the course of these activities, several previous SEI publications have covered, in particular, the technical aspects of renewable energy technologies.

As pointed out above, it seems clear that implementation is now the key issue, and this is the focus for the papers in this volume. They were originally commissioned by the journal *Energy Policy* for a series on renewable energy appearing between January 1991 to September 1992. In view of the fast-changing demands on conventional energy supply to meet environmental imperatives, it seemed timely to reproduce here a selection of those papers with a new introduction and a revised concluding chapter by the Editor of the series, Dr Tim Jackson, a research fellow with SEI. It is our hope that this collection will complement the burgeoning technical literature, in providing a deeper understanding of the question of implementation, and in so doing, contribute an added impetus to realising the considerable potential which renewable energy has to offer.

Lars Kristoferson
Stockholm, June 1993

Editor's Introduction

As the twentieth century moves towards a close, the problem of providing an adequate, secure, and environmentally acceptable supply of energy for the needs of a fast developing world is amongst the most pressing of those facing human societies. While there is clearly scope for reducing energy demand – particularly through improved enduse efficiency[1] – especially in the so-called 'developed' societies, there will be a continued demand for high quality energy supply, particularly as poorer nations pursue their own development paths. In this context, there has been a renewed interest over the past few years in renewable energy technologies: technologies which convert ambient flows of energy through the environment into usable sources of end-use energy for the consumer.

Over the past decade, many of the renewable energy technologies – wind, solar and biomass technologies in particular – have passed through several generations of development, and are now in a position to contribute economically to global energy supply. Nevertheless, only a limited amount of new, renewable energy has actually been brought into commission, and it has become apparent, that a number of obstacles and impediments remain in the way of a wider implementation.

The purpose of this volume of papers is to address the question of implementation in detail, to examine the individual technologies from the point of view of realisable potential, and to pay particular attention to the economic, institutional and policy aspects of renewable energy. In the course of making this investigation, considerable information on technical aspects is also provided, and a number of case studies are presented which illustrate both technical and institutional aspects. But the primary aim of the book is to ask the questions: what is the realistic potential for renewable energy, what obstacles or impediments stand in the way of a greater realisation of that potential, and how may those obstacles be overcome?

The changing context

Renewable energy was once the basis for the existence of human societies. Times change. In the late 20th century barely 20% of world energy demand is met by sources classified as renewable.[2] Instead, human civilisation has developed, and become increasingly reliant on, a global energy supply infrastructure based on large-scale extraction, distribution and consumption of fossil fuels.

In geological terms, the scale and speed of this revolution has been staggering. Associated with it are increases in resource use, industrial production, chemicals manufacture, technological sophistication, standards of living, institutional complexity and population, which are equally startling. The increase in material throughput resulting from massive consumption of fossil fuels has presented environmental hazards on an unprecedented scale to threaten the civilisation dependent upon it.

Escaping such threats – amongst which we can count the potentially catastrophic global impacts of global warming, the regional degradation caused by acid emissions, and the local environmental impacts of toxic contamination from a wide range of substances – depends crucially on our ability to develop an economic system which is materially closed, apart from the sustainable use of renewable resources.[3] A significant part of the burden of this exercise will inevitably fall on our energy use and supply infrastructures.

To take only the two most obvious examples, energy-related activities are estimated to contribute at least 60% to the global warming of the atmosphere, and almost all of the problem of acid rain. More generally, the need to reduce the wide-spread dispersal of toxic and hazardous substances throughout the environment also has energy implications, in terms of the closure of material cycles and the substitution for toxic materials usage.

The historical development of society as an energy and materials intensive system does not in principle preclude later efficiency improvements which will reduce that intensity. Indeed, the movement in ecological systems generally (of which the human system can be regarded as some kind of special case) tends to be towards improved material closure.[4] Nevertheless, there are some strict physical limitations to improvements in efficiency of use.[5] Beyond such limits, there will always be a need for energy supply measures to meet the demands of a world whose complexity is almost unimaginably greater than the world in which a renewable energy supply structure previously held sway.

This then is the historical context in which the latter-day, 'modernized' renewable energy technologies are contending. From one perspective, it is not so much that contributions of renewable energy to the human economy have decreased. On the contrary, absolute contributions have actually increased within many countries. Rather, it is that the availability of fossil fuel energy has led to a huge increase in the energy intensity of civilisation over the last two centuries. The renewable energy conversion technologies (such as water and wind power) which were widely used only a century ago, were largely abandoned because their low power capture and relative inefficiency rendered them obsolete in the face of this increased energy intensity, and the vastly greater flexibility, mobility and availability of fossil fuels.

Generally speaking both the power capture and the conversion efficiencies of the modern renewable technologies are considerably higher than those of their ancestors. Were this not the case, it would scarcely be worth contemplating significant contributions from them, without substantial changes in the entire infrastructure of society.

Nevertheless, we should be under no illusions about the demands that are being made on the returning renewable option. The world renewable energy left behind almost two centuries ago is changed beyond all recognition. The physical demands placed on the newer conversion technologies are therefore considerable. Equally importantly perhaps, these technologies will have to compete in a world which has been transformed as much by the institutions and politics of conventional energy supply as by the technological sophistication of the society to which it has given rise.

From the point at which humankind began to rely on fossil fuels, the balance of political and economic power in the world has been determined, at least in part, by the extent to which different nations did or did not have access to or control over fossil fuel reserves. During the latter period of the twentieth century the ramifications of this infrastructure for the supply of energy have delivered several stinging messages to the political world. Major indications of the geopolitical implications of energy infrastructure were provided by the oil price shocks of 1973/4 and 1979. The world recovered from these initial shocks, and even made some efforts to cushion the blow of future impacts.

Between 1970 and 1987, for example, the average energy intensity of the gross domestic product (GDP) in OECD countries fell by 23%, and the oil intensity by 35%.[6] Various national initiatives – for instance the energy programme of the Carter administration in the US provided direct incentives both for research and development of renewable energy and for investment in renewable technologies, indicating that governments were more prepared than they had previously been to pay serious attention to non-fossil fuelled energy options. But none of these efforts seriously undermined the supremacy of fossil fuels as the basis of world energy supply in the twentieth century, so that the economic markets were able to countenance an oil price collapse in 1986 which reflected nothing of the vulnerability of international security to resource needs, nor indeed of the mounting environmental concern over the increasing use of conventional energy supplies.

In 1989, the World Commission on Environment and Development highlighted four particular environmental risks of a high energy future based on conventional fuels:

- the 'serious probability' of climate change as a result of the build-up of atmospheric greenhouse gases from the combustion of fossil fuels
- urban-industrial air pollution from the combustion of fossil fuels
- acidification of the environment from the same causes and
- the risks associated with operating nuclear power reactors and the problems of radioactive waste disposal.

The Commission concluded that 'every effort should be made to develop the potential for renewable energy, which should form the foundation of the global energy structure during the 21st Century. A much more concerted effort must be mounted if this potential is to be realised.'

Four years later, in January 1991 the United Nations sanctioned military intervention against Iraq over its annexation of Kuwait, one of the richest oil-producing nations in the Middle East. During the period of uncertainty which preceded the Gulf War, oil prices rose from a pre-crisis level of $15/bbl to reach $40/bbl at one point, the highest level since the 1986 price collapse.[7] Estimates of the costs of the war might have added well over $60/bbl to this price according to some[8] – but these are 'shadow' costs which are not of course borne by oil consumers or oil producers but by the tax payer's contribution to defence.

Whether or not such strategic investment has been worthwhile in the case of the Gulf War probably depends on perspective. Significantly for short-term decision-making, oil prices returned to less than $20/bbl on the 'successful' conclusion of the Gulf war, and certain of the oil-producing nations – Saudi Arabia in particular – increased both their output and their production capacity in its wake.[9] The real 'price' of strategic military intervention in the Gulf may rather be in human terms, in environmental terms and in terms of long-term international stability.

Perhaps it was the light of this experience which led in part to the adoption of Principle 25 of the Rio Declaration at the United Nations Conference on Environment and Development (UNCED) in June 1992. This Principle recognises explicitly that 'peace, development and environmental protection are interdependent and indivisible', an almost unprecedented international recognition of a new approach to strategic and environmental security. Despite this recognition, the UNCED process did not escape the political ramifications of the international energy supply infrastructure.

This was illustrated most clearly by the deliberations surrounding Chapter 9 (on Protection of the Atmosphere) of Agenda 21 – the conference's voluminous blueprint for sustainable development in the 21st Century. Following in the footsteps of the WCED report, and motivated in part by the emerging United Nations Framework Convention on Climate Change, the draft version of Chapter 9 prepared by the Preparatory Committee in New York in April 1992 contained no less than 15 references to new and renewable sources of energy in as many pages of text. The draft document called on countries, for example, 'to increase the contribution of environmentally [safe and] sound energy systems to the energy supply and consumption mix, [in particular]/[including] through the promotion, distribution and development of renewable sources of energy'.

The multiplicity of references to renewable energy in the draft document persuaded a number of oil-producing nations to insist that the entire chapter was presented in brackets[10] to the June summit. By the time it was finally adopted, the passage quoted in draft above had been somewhat weakened, calling for policies or programmes 'to increase the contribution of environmentally sound and cost-effective energy systems, particularly renewable ones.'[11] Nevertheless, nine of those fifteen references to renewable energy remained in the final version of Chapter 9, despite continued attempts by the oil-producing nations to have them removed. Saudi Arabia, in particular, formally placed on record its reservations to the chapter in the final Plenary Session of 14th June.[12]

The question of potential

In a perverse sense, such deliberations suggest that renewable energy technologies represent a real threat to conventional energy supply. And yet the evidence from existing contributions from renewable energy begs the question: is this really likely?

A great deal of attention is paid, at an increasingly international level, to renewable energy – particularly in the face of the environmental impacts of conventional sources of energy. But is it not the truth that very little is actually happening? Whatever might be the declarations of non-binding international agreements, whatever the intent of the Brundtland Commission, whatever the scientific and technical consensus on the preferability of renewable energy technologies over fossil fuel technologies, or the efforts of individual nations to increase the contribution of energy supply from renewables by a few percentage points, the truth is that the present contribution from genuinely new, renewable sources such as wind power, solar power, wave power, small-scale hydro, tidal power, geothermal, or modernised biomass and biofuel technologies is miniscule in comparison to world energy demand.

Several national governments have adopted targets for implementation of renewable energy technologies. The Dutch government, for example, has had since 1986 a target[13] to meet 10% of electricity demand through renewables by the year 2000. But progress towards such targets has been slow. President Carter's target of 20% by the year 2000 for renewables in the US, fell heavily under the impact of subsequent Republican governments and the shorter-term, market-dominated policies of the 1980s. Towards the end of that decade government projections estimated only a 9.5% contribution from renewables by 2000 compared with around 8% at the moment.[14]

Still the optimistic note continues to be sounded. In May 1992, the European Commission presented its proposals[15] for a Council Decision concerning the promotion of renewable energy sources in the European Community (EC), calling for a trebling of the percentage contribution of renewables to electricity supply and a doubling of the contribution to energy supply in the EC by the year 2005. In the same year, the House of Commons Energy Committee in the UK declared itself 'much more confident about the prospects for use of renewable energy' than it had been in a report published less than three years previously,[16] and this confidence was reflected in a recently published report from the Renewable Energy Advisory Group[17] which proposed significantly higher targets for implementation than had previously been accepted by the government. In the US, a group of non-governmental lobby organisations published an influential technical study indicating the potential for renewable energy to meet over half of a drastically reduced energy demand by the year 2030.[18]

What is to be made of these contradictory claims? Does renewable energy really offer the potential its protagonists claim for it: significantly to displace conventional fuel supplies in the future energy mix, and thereby reduce significantly the environmental burden of human energy consumption? If it does offer such potential, then why is development taking place so slowly? Is it possible to speed up that development? Is it at all feasible to realise the Brundtland Commission's ambitious claim that renewables should be the 'foundation' for energy supply in the 21st Century?

These were the questions set out to be addressed in a series of articles published in the journal *Energy Policy* during 1991 and 1992. This volume has collected around twenty papers from that series[19] to provide a detailed attempt to answer the questions posed above.

Summary of contents

The early papers in this volume (Part I) cover the individual renewable energy technology types from a broad perspective, addressing the technological aspects of improved power capture and conversion efficiency, but also providing a broad overview of costs, environmental aspects, and institutional factors for each technology category.

Grubb (Chapter 1) provides a broad overview of renewable technologies, illustrating some of the particular difficulties associated with implementation by reference to wind energy in the UK. **Hall** (Chapter 2) plays the guide for a trek through the variegated terrain of biomass energy. The diversity of sources, of conversion technologies, and of end-uses provides a startling illustration that renewable energy is a far less homogeneous group of technologies, than those associated with fossil fuel conversion.

This impression is reinforced in the chapters which follow. **Kühne and Aulich** (Chapter 3) make a careful assessment of the technical and economic parameters of various solar conversion technologies. They discuss recent cost reductions for photovoltaic cells, and also address the economics of storage. **Gipe** (Chapter 4) presents the twin colours of wind energy: the experiences of more than a decade of development in Denmark and California. It was in these countries that modernized wind energy technology climbed hesitantly out of infancy and learned to stand on its own two feet.

There is a clutch of broadly aquatic technologies (hydro power, tidal power, wave power) which possess perhaps a certain family likeness amongst the heterogeneous renewables. Nevertheless, as **Falnes and Løvseth** point out (Chapter 5), there are a number of different technological designs even with the field of wave energy. **Sims** (Chapter 6) argues the case for hydroelectric power. He highlights the shared resource problem of developing both water resources and the land required for damming large reservoirs. Both of these papers point out the characteristics of renewable energy projects as long-life, capital intensive investments and call for appropriate economic frameworks in which to account for the long-term benefits associated with them. Many of these themes are echoed in **Baker**'s assessment of the tidal power option (Chapter 7).

Geothermal energy is a kind of 'honorary' renewable sharing most in common with other renewables in that it is different again from all of them. **DiPippo** (Chapter 8) enlightens us on the technological complexity, highlighting the complexity and site-specificity of economic feasibility assessments by comparison with conventional sources.

If there has been any technological omission from this series of papers it is perhaps the absence of detailed consideration of geothermal hot dry rock (HDR) technology and energy from waste, both of which, whilst not strictly renewable, have generally been counted amongst the renewable technologies. So far as HDR is concerned, Grubb (Chapter 1) for instance argues that it may be one of three 'infant' renewable energy technologies which tap a very large global resource base. At the same time, the technology is probably less assured than almost any other renewable energy technology, and the economics seem precarious at the moment. Nevertheless, the interested reader can certainly find a number of sources which will provide specific information, some of them referenced in Grubb's paper.

The omission of the energy from waste incineration option may be seen as more serious by some committed enthusiasts. Derivation of energy from incinerated waste is certainly better than incinerating waste with no energy recovery, and potentially more benign than landfill. On the other hand, it can certainly be argued that energy from waste is not really renewable because it does not utilise truly ambient energy flows, but rather energy flows which are contingent on particular materials consumptions patterns by society. In addition, energy from waste does not share the same potential environmental advantages of other renewable technologies, once emissions of a wide range of toxic substances to which a large-scale waste incineration programme might commit us are taken into account. Further, the development of a potentially hazardous technology with an appreciable economic inertia[20] operates as a disincentive to recycle wastes, or simply to reduce them at the source. This latter point is explicitly recognised, for instance by the House of Commons Energy Committee in the UK, who suggest that the 'harmful environmental impact of large-scale waste burning is potentially the greatest of any of the renewables' and recommend that 'consideration be given to the introduction of environmental regulations and emission limits which will enable waste incineration and recycling options to be more realistically compared'.[21] Nevertheless, the interested reader will be able to find a number of publications which deal more sympathetically with energy from waste than I have done here.

Part II of this collection examines questions of feasibility and system integration. **Mortimer** (Chapter 9) discusses the 'energy analysis' of renewable energy technologies. Energy analysis is a safety net for feasibility. It would be unfortunate to promote technologies which consumed more (fossil) energy than they produced, by virtue of high energy requirements in construction. This chapter provides a summary of data on the 'net energy requirements' of a broad range of renewable energy technologies, but also discusses the limitations of this data, and the need for updated studies. **Grubb** (Chapter 10) provides a careful analysis of the integration of renewable energy technologies into existing electricity supply systems, disputing the argument that electricity storage is necessary before 'intermittent' renewables can make a large contribution. **Winter** (Chapter 11) continues the themes of feasibility and integration, discussing in particular the long-term need for hydrogen storage as a means to a truly renewable energy supply system.

Renewables and development is the theme of Part III of the book. **Hall, Rosillo-Calle and de Groot** (Chapter 12) report some extensive research in the implementation of renewables in developing countries. **Rady** (Chapter 13) proposes principles for the implementation of renewables in developing countries, **Palmer** (Chapter 14) contributes a salutary tale from Bangladesh, and **Foley** (Chapter 15) warns against technological imperialism in the design of development assistance programmes.

The final part of the book is dedicated to policy aspect and the development of strategies for implementation of renewable energy technologies. **Flavin and Lenssen** (Chapter 16) present a comprehensive overview of different policy options for implementing renewable energy in the context of an energy efficient society. One almost unanimous call from the contributors to this series has been for the internalization of the environmental costs of energy supply. In **Hohmeyer**'s contribution (Chapter 17), this call is made explicit through an incorporation of estimated environmental costs into the costs of electricity supply options. **Elliott** (Chapter 18) examines the particular case of renewable energy development in the UK, under the impact of the recent privatisation of the electricity supply industry. **Grubb** (Chapter 19) discusses the policy and political aspects of renewable energy technologies, highlighting in particular the research and development needs, and the mechanisms available to address what he calls a 'failure of vision' in implementing renewable energy.

What is immediately striking from a closer examination of the various aspects of renewable energy is the often stark contrast between different technologies. The technology involved in small and large scale-hydro power bears a reasonably close relation to the technology of tidal barrages, and even to some of the manifestations of the chameleon wave energy. But these technologies are in a group apart from wind turbines, with its terminology of hub heights, blade fatigue, and wake interactions. And what common ground can there be between any of these technologies and the silicon cell technology of photovoltaics?

Amongst conventional technologies, the parameters of the energy supply problem are relatively clear, well-defined, and almost transferable between fuel types. Experts possess more or less the same educational background, can be trained in more or less the same technical and management courses, and are more or less transferable between different companies and different fuel types. The accumulated body of expertise of the individuals bolsters the level of technical proficiency of the whole. Take a group of delegates from the major energy supply companies, and put them in a room together. From steam turbine technology to fossil fuel pricing mechanisms, they would speak more or less the same language. Perhaps more importantly, the voice of the fossil fuel lobby, when it sounds in the corridors of power, is usually heard, if not exactly in harmony, then at least more or less in unison.

Amongst the renewables, life is considerably more variegated. Even the language is different. There is no common training ground for engineers or technicians, no universal terminology, no real transferability of knowledge. The thermodynamic, institutional, environmental, economic, social and institutional complexity and variability of the renewable energy conversion technologies are immediately obvious from any close examination of the different technologies.

Despite this complexity and variability, the later stages of the book indicate many common themes amongst these 'Cinderella' technologies.[22] Several distinctly similar phrases are heard in most of the renewables languages. Concerns about land-use, capital intensiveness, the unfavourability of financing structures and regulatory frameworks, and the intensely site-specific nature of costs and economic feasibility are pretty much common parlance, and these themes all turn out to be critical when it comes to the development of strategies for implementation of the technologies, discussed in the later parts of the book.

My concluding paper (Chapter 20) is designed to bring the analysis in the preceding parts of the book together. In particular, it addresses the all-important question of the potential for renewable energy, makes some assessment of the economics, and assesses the environmental impacts. Perhaps most importantly however, it discusses the institutional implications which are brought to light by the preceding chapters. In short, it sets out to answer the question which the papers collected in this book were designed to ask: do renewable energy technologies offer a realistic prospect of clean, long-term energy security for the 21st century, and if they do, how may that potential be realised?

Tim Jackson
London, June 1993

[1]T. Jackson, Least-cost Greenhouse Planning: supply curves for global warming abatement, *Energy Policy*, vol 19(1) January/ February 1991, pp35–46; E. Mills, D. Wilson, T. Johansson, 1991, Getting Started: 'no-regrets' strategies for reducing greenhouse gas emissions, *Energy Policy*, vol 19(6), pp526–542; K. Blok, E. Worrell, R. Cuelenare, W. Turkenburg, The cost-effectiveness of CO_2 emission reduction achieved by energy conservation, *Energy Policy*, vol 21(6), June 1993.

[2]Comprising around 14% from biomass (largely fuelwood in developing countries) and 6–7% from large-scale hydropower. In fact, there are an increasing number of areas in developing countries in which the fuelwood resource can no longer be thought of as renewable, because consumption rates are exceeding sustainable yields, and the Food and Agriculture Organisation has estimated (FAO, *Fuelwood Supplies in the Developing Countries*, Forestry Paper No 42, Rome, 1983) that by the year 2000 some 2.4 billion people may be living in areas where fuelwood is 'acutely scarce or has to be obtained elsewhere.'

[3]A detailed examination of the mechanisms for implementing such a strategy is presented in T. Jackson (ed), *Clean Production Strategies: developing preventive environmental management in the industrial economy*, Lewis Publishers, Boca Raton, Florida, 1993.

[4]E.P. Odum, Basic Ecology, 1983, John Wiley, New York.

[5]T. Jackson (ed) 1993, *op cit*, Ref 3, Chapter 1.

[6]Joyce Dargay, *Have low oil Prices Reversed the Decline in Energy Demand?*, Oxford Institute for Energy Studies, Oxford, UK, 1990.

[7]See Sheikh Ahmed Zaki Yamani, 'Oil price stability and free markets', *Energy Policy*, Vol 2, No 6, June 1992, pp 495–499; W. Goldstein, '1990: is this the third oil price shock?' *Energy Policy*, vol 18, No 8, October 1990, pp 686–688; A. Kemp, D. Rose and R. Dandie, 'Development and production prospects for UK oil and gas post-Gulf crisis', *Energy Policy*, vol 20, No 1, January 1992, pp 20–29.

[8]A. Tonelson and A. Hurd, 'The real cost of Mideast oil', New York Times, 4 September 1990, cited in Flavin and Lensson, Chapter 16.

[9]*Op cit*, Ref 7, Kemp *et al.*

[10]The procedure used to denote undecided upon text.

[11]In fact, this is hardly the same thing at all as the initial version. Without the conjunction of the word 'contribution' and the phrase 'to the energy supply consumption mix', this watered-down version might easily be construed as a call for increased energy consumption rather than a change in the supply mix!

[12]See *Earth Summit Bulletin*, No 13, 16 June 1992, Island Press/International Institute for Sustainable Development.

[13]*A Clean Environment: choose it or lose it*, The National Environmental Policy Plan, Ministry of Housing, Physical Planning and Environment, The Hague, Netherlands, 1989.

[14]*Long-range Energy Projections to 2010*, US DoE, Washington, DC, USA, 1989.

[15]European Commission, *Specific Actions for Greater Penetration for Renewable Energy Sources* – ALTENER, DGXVII/122/92-EN Rev 1, May 1992, draft.

[16]House of Commons Energy Committee, *Renewable Energy*, Fourth Report, Session 1991–92, March 1992, HMSO, London.

[17]Renewable Energy Advisory Group, *Report to the President of the Board of Trade*, November 1992, published as Energy Paper 60, HMSO, London.

[18]Union of Concerned Scientists, Alliance to Save Energy, American Council for an Energy Efficient Economy, and Natural Resources Defence Council, *America's Energy Choices: investing in a strong economy and a clean environment*, 1991, Cambridge, Mass.

[19]Included in this volume are two papers (Chapters 1 and 19) which were not part of the original series but were published in *Energy Policy* immediately prior to the commencement of the series. These papers are included in this collection because they clearly address the important question of the overall potential for implementation of renewable energy.

[20]This inertia will be exacerbated as landfill becomes scarcer, and gate fees increase.

[21]*Op cit*, Ref 16, p xxxi.

[22]In Chapters 1 and 19 Grubb describes the renewables as the 'Cinderella options'.

Acknowledgements

I owe a debt of gratitude to all of the authors who contributed to the original series of papers in **Energy Policy**, and to all those who provided help and advice during its compilations and writing. In particular, I would like to thank Catherine Mitchell and Jim Sweet who gave me invaluable assistance in the early stages, Michael Flood, Michael Grubb, David Hall, Bent Sørensen and John Twidell for their advice on subject matter and content, Michael Harper and Simon Roberts at Friends of the Earth for critical comment during the latter stages, and for their efficiency in providing me regularly with updated information. I would also like to acknowledge the financial and intellectual support afforded me by my associations with several institutions during the process of compiling these contributions, namely: Earth Resources Research (London), the Centre for the Study of Environmental Change at the University of Lancaster, and the Stockholm Environment Institute. I am particularly grateful for the opportunity to have participated in an SEI seminar on Emerging Energy Technologies, which helped to crystallise the conceptual arguments in the final chapter. I am also indebted to Arno Rosemarin, the information manager at SEI for his negotiating powers and editorial advice, to Gordon Goodman, Mike Chadwick and Lars Kristoferson at SEI for their interest and encouragement, and to Robin Frampton, Lynda Connock and Caroline Stevens at Butterworth-Heinemann for their efficiency in facilitating both the original series and this publication. Finally, recognition should go to Nicky France, editor of *Energy Policy*, who was responsible for initiating the project in the first place.

Part I: Renewable Energy Technologies

Chapter 1

The Cinderella options

A study of modernized renewable energy technologies
Part 1 – A technical assessment

M.J. Grubb

This paper examines the status of and prospects for renewable energy technologies. Wind energy is taken as an example of the negative myths which impede renewable energy developments. The paper then emphasises the great diversity in renewables: different technologies are at very different stages of development, and are suited to different countries, locations and applications. Further technology development is very important, but nevertheless it is argued that the prospects for obtaining large-scale renewable supplies are good, especially in the industrialised countries. Sufficient evidence exists for renewables to be taken much more seriously in energy scenarios and policy developments.

Keywords: Renewable energy; Energy policy process; Supply

Renewable energy is an enigma. Everyone is in favour of it, but few take it seriously. Most agree that renewable energy research deserves more money, but the funding remains small compared with much more speculative technologies such as nuclear fusion. Renewable energy is praised for its environmental advantages, whilst environmental objections are raised increasingly as the major constraint.

There are two main attitudes towards the prospects for and importance of non-hydro renewable energy. One, widely expressed throughout the environmental community, is that in the long run renewable energy will save us all from the unsustainable consequences of relying upon fossil fuels and nuclear power. The Brundtland Commission echoed this in stating that renewable energy 'should form the foundation of the global energy structure during the 21st Century'.[1]

The other common attitude is that in the short to medium time horizon relevant to the real world of industrial and political policy formation and investment, non-hydro renewable sources are essentially irrelevant: that for the foreseeable future their contribution will remain marginal. This attitude is reflected in the levels of research, development and demonstration (RD&D) funding, with expenditure on the best supported of renewable technologies being a small fraction of direct government expenditure on fossil and nuclear sources (see Figure 1) and an even smaller component of total public support (see Figure 2).[2] It is apparent in the institutional balance, with the major international institutions devoted to nuclear power having no counterparts for renewable energy.[3] It is evident in the absence of renewable energy from general energy policy development – to take but two examples, the EC documents discussing the projected internal energy market,[4] and the original draft proposals for electricity privatization in the UK.[5] Above all, it is demonstrated by mainstream energy forecasts, which in almost every OECD country project non-hydro renewable energy contributions still at a few per cent of supply decades into the next century.

Taken together, these two attitudes suggest that one day the world must run on renewable energy, but that the timescale on which it will even begin to

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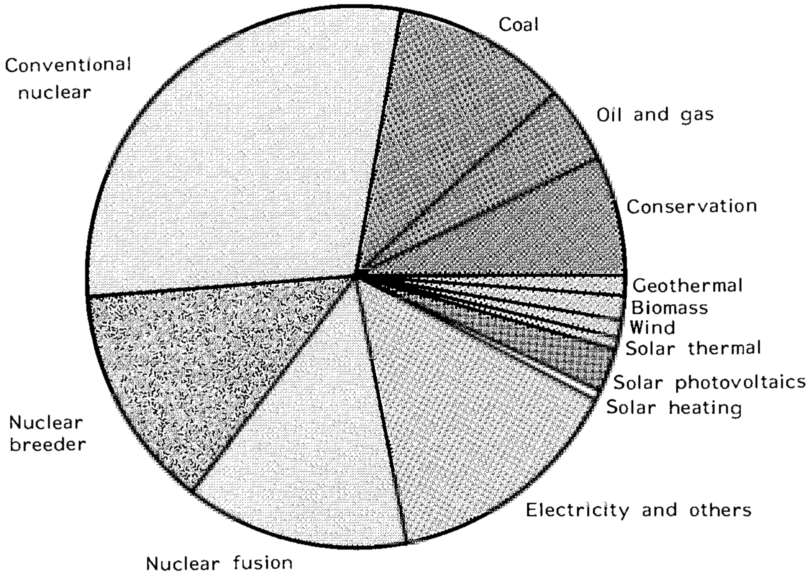

Figure 1. Total IEA direct government RD&D expenditure (1988 US$m).

make a significant contribution is not foreseeable. This is unfortunate. It is also wrong.

Currently, renewable energy sources probably account for somewhat over 20% of primary world energy supplies (input equivalents), this being dominated by biomass (14%)[6] and hydro (6.7%).[7] The contributions from passive solar drying and heating are significant but these are generally considered as incidental gains. Active solar water heating is very important in some countries in displacing commercial fuels,[8] and photovoltaics and wind make significant contributions in special markets, eg for communications and pumping. For none of these applications are useful statistics available.

Biomass use is dominated by non-commercial fuels for open-hearth combustion, especially in de-

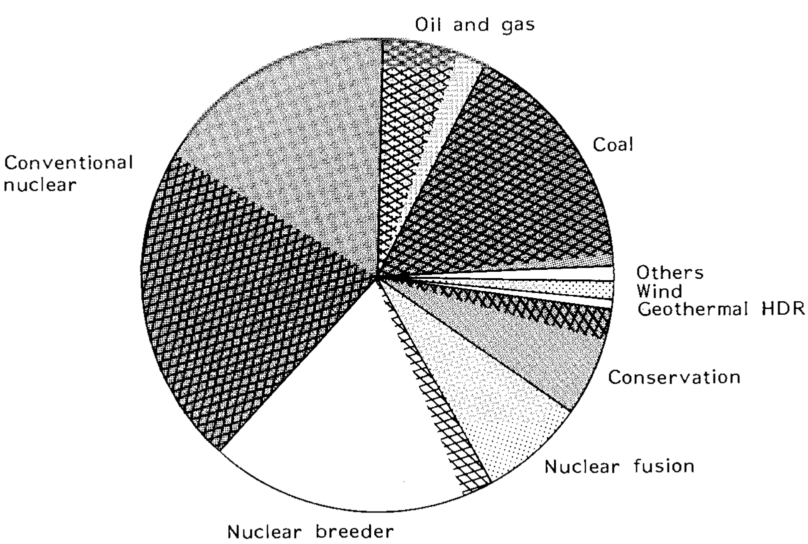

Figure 2. Total UK public sector expenditure on energy RD&D (1985–86 £m).

Hatched areas = spending by nationalized industry
Remainder = direct government expenditure
Others: wave, geothermal aquifer, solar, biomass, tide, hydro/general, ETSU services.

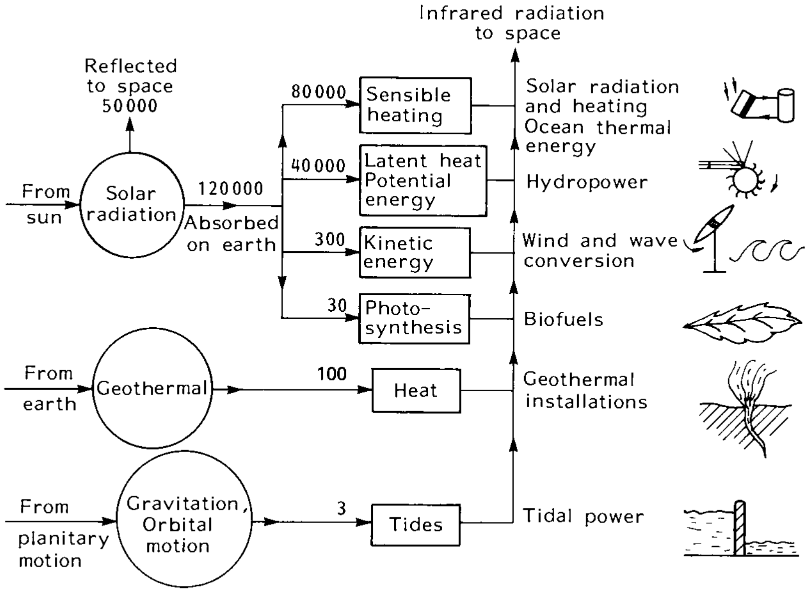

Figure 3. Global renewable energy flows (units TW 10^{12}W; commercial energy consumption = 10.5 TW).

Source: Twidell and Weir, *op cit*, Ref 9; (data for photosynthesis amended from ref 11).

veloping countries, a use which cannot expand much further. Large-scale hydro is an established form of centralized power production, with probably limited scope for further developments in industrial countries because of environmental constraints. This paper concentrates upon the prospects for commercial non-hydro renewable sources using modern technologies, from which contributions are currently very small.

Despite this, it is argued that non-hydro renewable energy technologies can no longer be relegated to the backwaters of the industrial and policy process: a number are already sufficiently developed and commercially attractive, or soon will be, and their impact could be swift and substantial. Yet the opposite extreme does not hold either: non-renewable energy will remain important throughout the next century, and attempts to promote visions of a world run entirely on renewables are misguided and ultimately damaging.

The paper is divided into two parts. Part 1 assesses the technical prospects for renewable energy, based on resource constraints, known technology and reasonable technological expectations, with minimal attention to its current market situation and majority expectations. Part 2 (Chapter 19 in this volume) then considers the current situation, analyses the reasons for various attitudes towards renewable energy sources, and outlines a number of policy issues. The paper concludes that a revolution of attitudes towards renewable energy in the policy communities of industrial countries is required and is indeed inevitable in time. The speed and impact of the transition will depend largely upon policies adopted over the next decade. The aftermath of the process will not be a panacea for all our energy ills, but a situation in which the large economic potential for renewable energy sources is accepted, with recognition of both benefits and drawbacks: a situation, in other words, in which they are treated on a par with conventional sources as a central component of broadly sustainable energy economies.

The renewable resource base

Renewable energy flows are illustrated in Figure 3.[9] The rate of solar input is nearly 20 000 times human energy consumption. Of this, 30% is immediately reflected and nearly half is converted directly to heat and re-radiated as infra-red radiation. The great majority of the rest is taken up in the hydrological cycle, and the tiny fraction of this which falls as rain or snow over high ground and can be captured in run-off forms the hydro resource, estimated at 10–30% of current world energy use.[10] The atmospheric heat gradients drive the winds, which dissipate power at about 40 times the rate of human energy consumption; the amount converted to waves is roughly equal to human consumption. Finally, some 3 500 EJ/year – some nine times human consumption – is absorbed in photosynthesis every year.[11] To this list, in principle, should be added the very large ocean resources arising from heat gradients and ocean streams, the osmotic resource arising from the differing salt content of river and sea water, and the vapour pressure resources from the heating of desert air.

The solar resource represents the maximum physical energy available. This is not the case for tidal and geothermal energy.[12] Tidal energy schemes work by increasing the dissipation of tidal energy at shorelines, so the natural rate of dissipation – the number in Figure 3 – does not represent the theoretical limit. Geothermal energy similarly does not rely on the natural heat flow, but generally extracts heat which has accumulated over centuries in water (aquifers) or hot rocks as a result of tidal friction and natural radioactive decay, and extracts it much faster than it can be replaced.

Consequently geothermal energy is not a renewable source, although it is usually included as such. It is most easily exploited from aquifers, but the resource is probably fairly small.[13] Pressurized brines, at greater depth, present a largely unknown resource. The theoretical resource from tapping hot rocks or even magmas is essentially infinite – the heat contained in the top few kilometres of rock worldwide is larger even than world uranium reserves exploited with breeder reactors – but only a very small portion of this could conceivably be tapped. For these, the technical and resource characteristics are too uncertain to allow more meaningful estimates.

It is clear that, physically, renewable and geothermal energy resources are more than adequate to meet any conceivable human needs. The question is, can these resources be tapped in an acceptable manner without excessive costs?

Technologies for tapping renewable energy flows which have attracted most interest are listed in Table 1. The list is by no means comprehensive and each broad category can be subdivided into numerous detailed technologies.[14] Nevertheless, it serves to emphasize that renewable energy technologies cover a very diverse range: from ideas still on the drawing board to well-developed technologies; from local and small scale systems, through intermediate scale dispersed and centralized applications, up to the large civil engineering projects of hydro and offshore developments, and even solar satellites.

This paper does not attempt even a cursory review of the status and prospects for such a large number of distinct technologies. Instead, it focusses initially upon one source in one country, and then seeks to expand the observations first to incorporate other technologies, and then to an international view.

Wind energy in the UK

A case study

The country chosen is the UK, which illustrates a number of issues clearly. UK resources of the most familiar forms of renewable energy, namely hydro, geothermal aquifers, and solar, are relatively poor. A reasonable level of data on the less familiar forms is now available, due largely to efforts of the Department of Energy's Energy Technology Support Unit (ETSU). However, renewable energy has never featured significantly in the Department's mainstream discussion or projections. It is thus especially interesting to see how Britain[15] fares on a close analysis of the potential for renewable sources.

The technology chosen for detailed consideration is wind energy. This is a prime example of a renewable technology which most people have found difficult to take seriously, because the wind appears to be such a feeble and variable resource. Nearly all studies during the 1970s concluded that wind could not be a large-scale source of economic power, and the Department of Energy ranked wind energy as one of the least promising of renewable energy technologies. Hoyle claimed that to meet Britain's electricity needs, windmills 'would have to cover more than half the area of all England', and '. . . the number of serious accidents would probably run into hundreds of thousands each year'.[16]

For many people, wind energy retains the image of a primitive, mediaeval technology not fit for the modern age. And yet, the technology has advanced very rapidly in the last decade, and there have been many favourable assessments. Less than 10 years after the above assessments, the Department's programme managers wrote that 'the Department of Energy now regards large scale generation from wind energy as a serious option',[17] with an estimated contribution by 2025 of up to 10% of current generation.[18] Its potential is still in dispute but the change in assessment does seem sufficient to raise questions about the assumptions and validity of some earlier assessments of renewable energy's potential.

Five main reasons have been advanced in claiming that the realistic potential for wind energy is very small:

- it is too costly;
- the technology is not reliable;
- the variability of wind energy means that it cannot be used as a major source of power without storage, which would be very expensive;
- the resource, after taking into account the

Table 1. Main renewable energy categories.

Resource technology	Energy product	Status
Hydro		
Large-scale	Electricity	Developed, often economic, widely deployed
Micro-hydro	E	Developed, usually economic, not widely deployed
Solar		
Passive heating	Heat	Developed, usually economic, mixed deployment
Active heating	H	Developed, variable economics & development
Thermal electric	E	Large centralised test stations: results not favourable
		Smaller modular units: commercially economic in favourable circumstances
Photovoltaic	E	Rapidly developing, varied projections
Solar ponds	E	Demonstrated, not economic at present
PV–hydrogen	Fuel	Components proven; economics speculative
Wind		
Pumping	Mechanical	Developed, deployed in remote areas
Onshore turbines	E	Recently developed, still improving, early deployment stage
Offshore turbines	E	Some trial stations, varied projections
Biomass		
Agricultural & Forest Residues & surpluses		
Domestic & Industrial Wastes		
Biomass crops		
Direct combustion	H	Widely used but inefficient
Decomposition/hydrogenation/ fermentation etc	F	Various demonstrated, usually not economic at present
Gasification	F, E	Unproven but promising
Geothermal		
Aquifiers	H, E	Proven, often economic
Hot dry rock	H, E	Exploratory schemes, mixed results
Tidal		
Estuary Dams	E	Proven; economics depend heavily on financing assumptions
Streams	E	Speculative
Wave		
Shore-based	E	Test stations, favourable results
Deep water	E	Wide variety of devices; pilots but no prototypes tested
Others		
OTEC; Dew point energy; Salt gradients; Solar satellites		

siting constraints upon wind turbines, is small;

- the lack of any commercial development proves the case.

Let us consider these in turn.

Myth 1 – wind energy is much too costly

The 20th century has seen occasional attempts to modernize wind energy technology, but there were no concerted efforts until the mid-1970s, when several government programmes started to develop very large turbines. Much was learned, but most projects ran into substantial technical problems and high costs; a detailed assessment of two of the leading contenders in 1983 concluded that the energy would cost much more than from conventional options.[19]

A second phase of development, from 1982–85, was dominated by the creation of a market for small and medium sized machines in the USA, with a favourable regulatory regime combined with generous Federal and State tax incentives which made wind energy in some areas – particularly California –

an attractive private investment even at the then high costs. Installation rates in California rose from 10 MW/year in 1981 to 400 MW/year in 1984, with a cumulative investment by 1986 of about $2 000 million. In this brief period the mean size of commercial units doubled, performance improved dramatically, and costs fell sharply, mostly as a result of applying advanced materials and control systems and a better understanding of wind turbine dynamics and stresses.

The fall in oil prices and removal of tax credits then greatly tightened the market at a time when several large companies had put substantial capital into new machines, leading to further cost and price cuts.

In Denmark, one of the major manufacturers, wind energy is regarded as a major economic resource, with 350 MW installed by 1990 feeding an official target of 2 000 MW (to generate 10% of electricity) by 2000.[20] In 1988 the UK's Central Electricity Generating Board (CEGB) startled some observers by stating that at very good sites in Britain, modern wind turbines could generate electricity more cheaply than either nuclear or coal stations.[21] Avenues expected to give further substantial improvements have been identified.[22] However, the CEGB and others contended that the resources – at competitive costs – were small and the technology was still unproven.

Myth 2 – wind energy is not reliable

The track record of many early Californian wind farms has been appalling. With tax credits so high and time-dependent, machines were rarely adequately tested before installation. Many of the early installations were by companies that knew more about tax management than engineering, and soon broke down; even the more serious companies were for a time almost 'doing their R&D in the field'. Machines were often sited carelessly and very densely, and some were sold on blatantly fraudulent promises. Lines of ugly, motionless machines stand in testimony to the mixed blessings of such hasty development.

But with the market base and finance of California, several companies gained rapid experience. Wind farms from the best manufacturers in the USA and Europe have had several years operation at more than 90% availability, with some above 95%. This is much *higher* than most large-scale steam plant. This has been possible in part because the small unit size limits the overall complexity of the system and allows a rapid product cycle in which the lessons from failures can be quickly incorporated. Furthermore, when problems do occur most components can be quickly replaced. It is much a young technology that the long-term reliability is still unproven, but even if the entire rotor and primary shaft have to be replaced, this can be done at about 10% of the initial installed cost. Mitsubishi now offer a complete 10-year performance guarantee on their turbines, a striking contrast to the cost-plus arrangements for most conventional power stations. A far cry from its unreliable image, the reliability of wind energy could be a strong selling point in commercial markets.

Myth 3 – variable therefore valueless

Windspeeds fluctuate on all timescales and most areas can have many days without winds. This makes relying on wind energy for remote applications very difficult. However, for sources integrated on to large power systems, the spectre of major economic penalties arising from variable power sources is largely without foundation. Demand on the CEGB system fluctuates by 10–15 000 MW every day, and few plants are available for more than 80–90% of the time: quite why it was ever assumed that the variation in output of a few thousand megawatts of wind energy should cause any problems is something of a mystery. In fact, analysts agree that wind energy is just as valuable as conventional sources for meeting baseload demand when the capacity involved is small relative to the system,[23] and preliminary CEGB studies a decade ago estimated that the system could absorb 'about 20%' of its energy from wind turbines without significant difficulties.[24]

The value declines with increasing penetration into power systems, in ways which depend upon the characteristics of the system and the geographical diversity of the wind energy. An approximate rule-of-thumb is that, for average conditions on sizeable thermal power systems, the marginal value declines by about 1% for every 1% of electricity demand supplied.[25] This crude rule is sufficient to reflect the broad conclusion of complex modelling studies that economic penalties will become significant if wind supplies more than 20% of the total demand, and become prohibitive at contributions of 40% or so.[26] These levels are of course extremely large in comparison with anything under contemplation today, and in most countries power system constraints are unlikely to be a limiting factor.

Myth 4 – wind energy resources are very small

This physical potential for wind energy is very large, because energy extracted by wind turbines is rapidly replaced from the upper atmosphere. In Europe, even after allowing for exclusion of obviously unsuitable sites (eg towns, forest areas, etc) the theoretical potential for wind energy was estimated by the European Commission at 4 060 TWh/year, some 2.5 times net current European (EUR-12) electricity generation,[27] more than one third (1 760 TWh) of this total being in the UK. The author, with more modest machine and siting assumptions, estimated a much smaller 'first order' British mainland resource of 760 TWh/year – still about three times current UK electricity consumption.[28]

Such 'first order' estimates give no more than a theoretical upper bound. They cannot take account of the more general constraints arising for example from the visual reaction to wind turbines. The many attempts to make a more meaningful assessment of the resource have resulted in a wide range of estimates, and have been generally unsatisfactory because they inevitably rely on largely subjective estimates of what constitutes 'acceptable' sites and siting densities. Many people, pointing to the size of wind turbines and concerns about noise, electromagnetic interference and other worries, believe that planning objections to siting will heavily constrain the practical resource. Others argue that wind farms can be made very attractive, that the other objections raised amount to no more than scare stories, and that wind will prove much more acceptable than conventional sources: and hence that planning procedures will simply weed out the bad and leave a large acceptable resource.

There is no right answer to the question of visual acceptability (other objections will rule out some sites but they are of secondary importance in determining the overall resource) so estimates are subjective. Figure 4 shows the mainland resource obtained for a number of different siting cases for wind energy in Britain.[29] The full resource spans the range from about 5% to over 70% of current British electricity demand. The majority comes from relatively windy areas in which the economic prospects look good. The message is not that the practical potential for wind energy in Britain is necessarily either small or large: it is a matter of choice.

Myth 5 – the lack of commercial development proves the case

This encouraging analysis contrasts forcibly with the negligible role of wind energy in the current electricity market, and in most future projections.

The single most important reason for this contrast is the pace of wind energy developments. The traditionally conservative utility business is used to technologies which measure in hundreds of megawatts and take a dozen years to plan and construct, let alone develop. The gulf between this and a technology which has passed through three complete phases of development and deployment within this time, and has a typical unit size around a thousandth of the traditional scale, could hardly be greater. Many utilities are simply unaware of the current state of the technology and find it hard to take seriously.

The sour taste left by some aspects of the US experience is another major factor. This has been compounded by the fact that the incentives which led to the 'Californian windrush' were restricted to independent companies, selling electricity to utilities (which were forced to buy it). It was felt that monopoly utilities would be reluctant to pursue wind energy, but this became a self-fulfilling phophesy, preventing the development of utility expertise and labelling wind energy as an 'independents' activity.

Added to this is the complexity of wind energy as an investment option. Its performance and economics depend crucially on all manner of siting conditions. Uncertainties over possible local impacts and a reluctance to accept that varying, non-dispatchable sources are as valuable as conventional sources are also important. These complexities, coupled with the speed of developments, mean that there are very few people indeed outside the wind industry itself with the expertise and confidence to judge investments.

In the UK, independent wind energy development in the 1980s was impeded by byzantine rate and tariff regulations (since reformed) which rendered most independent projects inevitably uneconomic.[30] In addition, the main base-load competitors of coal and nuclear power have in both received large government subsidies in one form or another. The lack of wind energy deployment in the UK during the 1980s was proof not of wind energy's inadequacies – though its newness is certainly a factor – but of various systemic biases in the electricity market.

Thus upon close examination, each of the objections to wind energy as a major power source appear to be either plainly wrong or at least seriously open to question. Despite the many and apparently powerful arguments – and in some cases ridicule – directed against wind energy in the 1970s, the 1990s may well see it start on the path to being a substantial component of Britain's electricity supply.

Technical lessons from the case study

A few general lessons can be drawn from this. One is that technology development is crucial, but that institutions are very bad at foreseeing it. The argu-

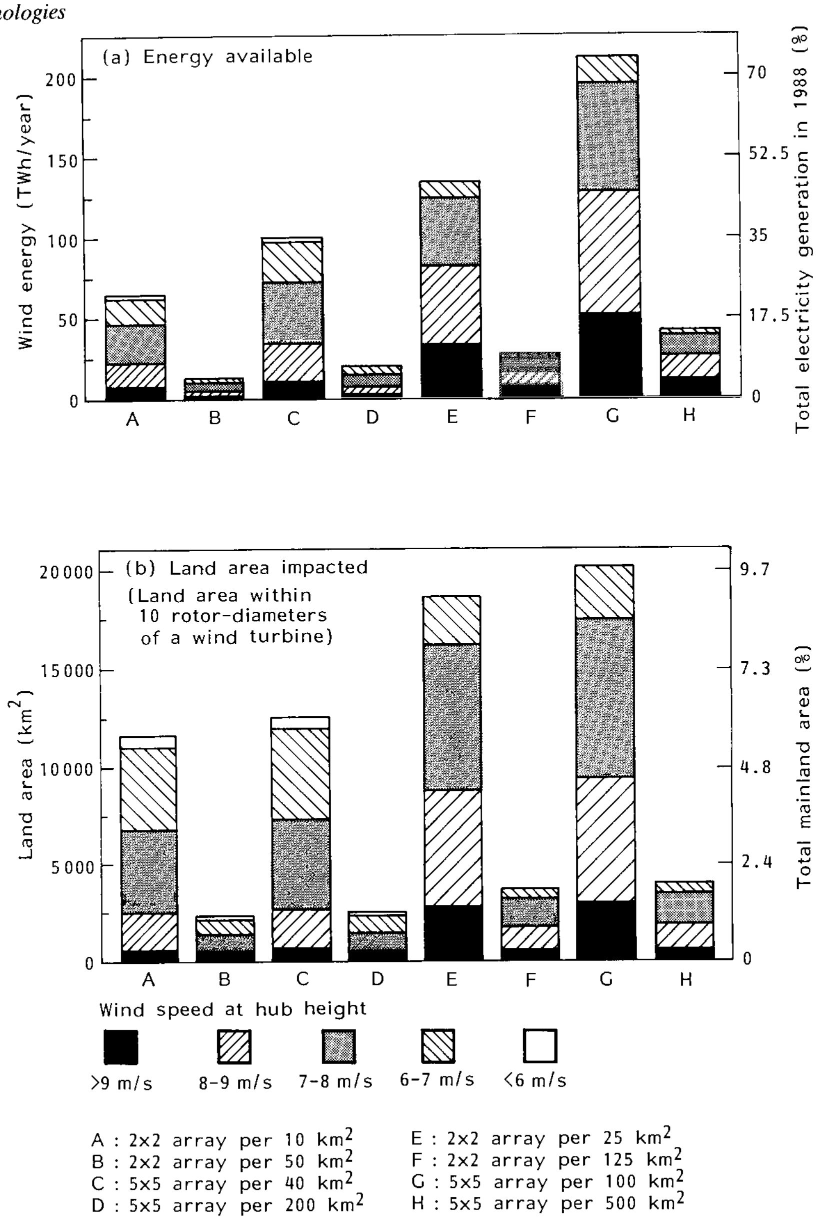

Figure 4. UK wind energy resources for different siting cases.

ments against wind were heavily founded upon the technology of the 1970s, which indeed was quite inadequate to provide a serious power source. Clearly there was great scope for improvement in a technology upon which very little had been spent, but few seemed prepared to think through the implications of this at the time.

The importance of technical development suggests that, in sharp contrast to the common assumption that renewables are somehow most appropriate for developing countries, their development and deployment is likely to be led in the industrial world. Only industrialized countries have the technological base, the capital, and the infrastructure required to push large-scale new developments in the energy sector. Expecting them to develop and demonstrate renewable technologies solely for application elsewhere not only assumes an unprecedented degree of altruism, but is managerially impractical. Furthermore, it leads to great suspicion in developing countries that they are being handed second-rate and unproven processes.

Of course, renewable sources are and will remain of crucial importance in underdeveloped regions. But the initial expansion of the more efficient technologies necessary if renewables are to contribute much to meeting future needs will be led elsewhere.

Another lesson which was anathema to the mental energy map of the time is that small-scale technologies are not necessarily at a disadvantage, and indeed that they have many advantages: they can be developed much more quickly and (still in the realm of speculation) may be easier to deploy rapidly on a large scale as well. The enthusiasts for the small scale, however, were (and some still are) equally reluctant to concede the point that advanced technology is required, and an integrated power system is essential, if the promise of many decentralized units is to be realized in practice.

Another general conclusion may be drawn from the extensive studies of wind integration on power systems. The high levels indicated for wind energy would become larger still if a mix of different variable power sources was considered (eg wind and solar); if the system has much natural energy storage (eg in the form of hydro power); or if deployment of load management technologies mean that demand can respond more flexibly to variations in the generation costs. Under these conditions, contributions from variable power sources could amount to over half the supply before additional storage would be required to utilize the power effectively.

The real difficulty comes in attempting to construct systems with all-renewable supplies (eg wind–solar–battery). The possibility of long periods without adequate input from the variable sources means that very large and expensive storage capacities are required if reliability is to be maintained; except for small-scale remote supplies, they appear completely impractical on realistic criteria.

However, with widespread availability of natural gas, and growing interest in gasification of biomass fuels for power generation (discussed later) most power systems are likely to have a substantial resource of low capital but moderate to high fuel cost plant on the system.

These are exactly the characteristics required to make an economic 'back-up' of variable power sources such as wind, wave, tidal and solar. To put it another way, if the system has much plant which is cheap to build but expensive to run, renewable electricity sources are very valuable as fuel savers. Variable or not, their short-term value of reducing coal and oil bills could transform into a long-term role of helping to limit emissions and spin out gas and/or biomass resources for the foreseeable future.

Other technologies

To what extent is wind energy in Britain an exception? Certainly, the resources are unusually good: more than two-thirds of the UK has wind resources in the top two of five categories in the European Wind Atlas,[31] and wind energy has been the main renewable beneficiary of the Californian developments.

The UK is certainly not well blessed with the more familiar kinds of renewable energy. Hydro, solar, and geothermal aquifer resources are all relatively poor. But there is a relative abundance of less familiar types in addition to wind. A 16-km long tidal barrage across the Severn Estuary could meet over 6% of electricity demand. With an estimated capital cost of some £8 000m and a 10-year construction time,[32] the energy cost depends heavily on the discount rate, ranging from 3–8 p/kWh over a discounting range of 4–10%. Two other large schemes along the west coast, at 10–40% higher costs, boost the tidal resource to about 15% of current electricity demand. The scale and payback times mean that these tidal schemes would require government support, and they could face strong environmental opposition. Numerous other smaller schemes, at similar energy costs but on a much less daunting scale, could provide another few per cent;[33] a private consortium is now backing an 800 MW barrage under the electricity privatization provisions.

Wastes with an energy content of about 25 mtce (compared with total primary energy requirement of about 200 mtce) are disposed of each year in the UK, of which 'about 5 mtce could be economically extracted for use as a fuel at current energy prices'.[34] Forest wastes could add as much again. If subsidies on agricultural land were applied to energy crops these could be viable, substantially increasing biomass resources.

Hydro, onshore wind, tidal and various forms of waste and biomass use, together with solar building design, can be considered as 'confident' renewables: the technical uncertainties are small and the costs not prohibitive.

Greater uncertainties surround other options. The exploitable offshore wind resource is estimated to be on the same scale as total electricity demand. Extensive deployment of wave devices off the north-west and south-west coasts might generate up to 20–40% of current electricity demand.[35] A number of unresolved engineering issues and the lack of any real experience means that the costs of offshore wind and wave are very uncertain, though desk studies place wind in the region 3–10 p/kWh and wave at 5–15 p/kWh.[36] Onshore, granite intrusions in the south-west and east Scotland give strong heat anomalies which could offer a substantial geothermal hot dry

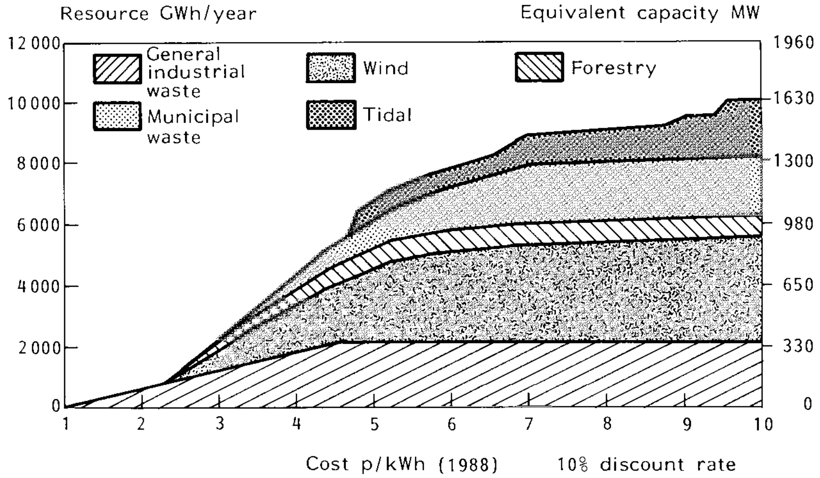

Figure 5. Renewable energy cost curves for the Norweb area.
Source: ETSU/Norweb, *op cit*, Ref 38.

rock (HDR) resource, though both are mostly in and around national parks and large-scale exploitation could face environmental disputes. A band of warm rocks runs across northern England and other, unmapped, heat anomalies may lie beneath sedimentary rock caps.[37] The UK is amongst world leaders in HDR technology but the prospects remain very uncertain, as discussed later.

Quantifying renewable energy resources is a complex task. Data are often poor, and are difficult to interpret: often the technological capabilities are still uncertain, the resources are very heterogenous (the energy density and economics may vary greatly according to local siting conditions), and the practical resources depend ultimately upon the practical siting density of conversion systems.

In the last few years a number of detailed studies have resulted in a good data base for estimating the practical bounds on UK renewable energy resources. An exceptional regional study attempted to quantify the potential for broadly 'confident' electricity-producing renewables for the region of the North-West Electricity Board (NORWEB) in England, which covers about 5% of UK land area and over 8% of population.[38] The study is a model of how a regional survey can be carried out and presented. Whilst acknowledging some of the uncertainties, particularly in estimates of the practical wind resources, the broad conclusion was that: '2500 GWh/year (about 12% of NORWEB's requirements) is believed to be potentially available at a cost of 3 p/kWh or less' (at commercial 10% discount rate).

The resource–cost curves developed, illustrated in Figure 5, show how the resource depended upon costs and the relative standing of the technologies considered. They highlight the conclusions that the majority of resources considered were not expensive compared with conventional options even on the strict commercial criteria considered: the report noted 'only that portion below about 5 p/kWh is likely to be of commercial interest . . . limiting the overall potential . . . to approximately 7000 GWh/year – about one third of NORWEB demand. The resource assessments are of course themselves uncertain (particularly for wind),[39] and neglect the more speculative contributions from HDR, wave, offshore wind, or energy crops.

Extrapolating such an approach to the national level, with a broader range of technologies, is fraught with difficulty. A national renewable energy cost curve for the UK, as published in a forthcoming report by the Watt Committee,[40] is reproduced in Figure 6. It illustrates clearly the range of renewable resources available and the broad way in which these resources depend upon costs. It seems to suggest the remarkable fact that about 250 TWh/year – roughly equal to current electricity generation – could be available from renewable sources at less than 5 p/kWh (5% discount rate – equivalent to 8–10 p/kWh at 10%).

Unfortunately, such a diagram gives a misleading impression of certainty, without the often speculative and subjective assumptions being clear.[41] Uncertainties abound both for the economic axis, because many of the technologies are poorly developed or analysed, and for the resource axis, because the resources depend so heavily upon assumptions about practical siting densities. When uncertainties are so large a different and more transparent approach is required.

Table 2 shows an attempt to summarize the poten-

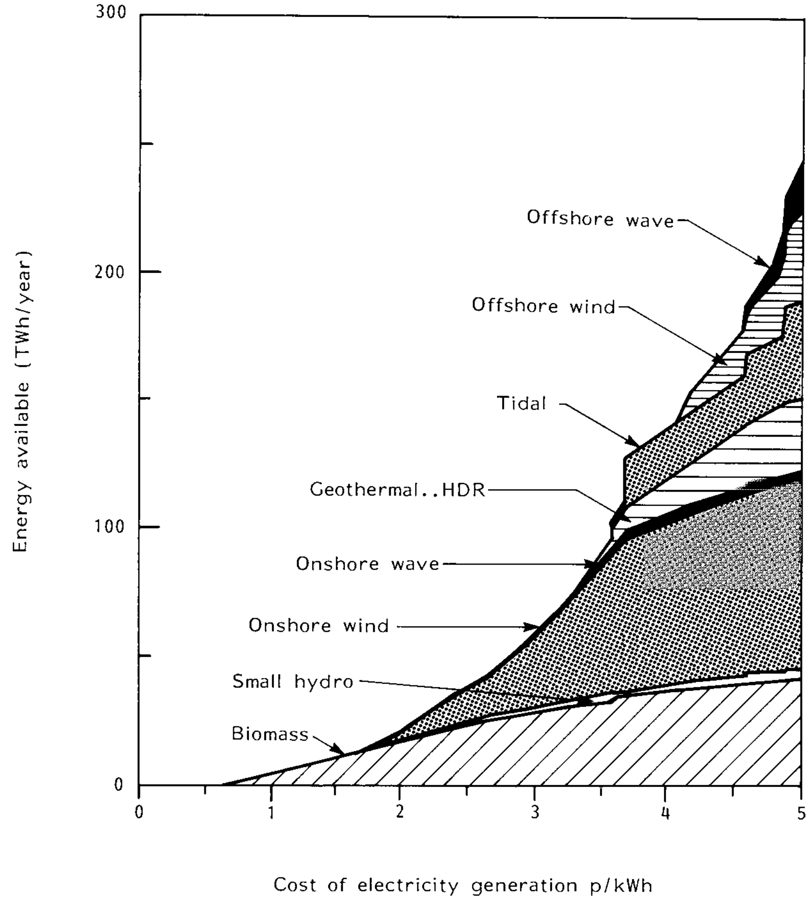

Figure 6. Estimated national resource-cost curves for the UK, (5% discount rate, 1987 costs).

Source: Watt Committee, *op cit*, Ref 40.

tial in a more objective and informative manner. Estimates of exploitable UK renewable energy resources are given for low and high siting density cases, along with the primary assumptions used and comments on the current status of the relevant technologies. The estimates are derived from an extensive survey of existing studies. The aim is to clarify the nature of the major uncertainties – and to highlight the sometimes extraordinary scope for varying conclusions given different approaches combined with our current ignorance. All the estimates are either below, or span, estimates of Technical Potential made by the Department of Energy.[42]

On one reasonable definition,[43] the 'confidently economic' renewable resource ranges from under 15% of current electricity generation, at the lower density, to over 40% at the higher density exploitation. By its nature, this figure makes little allowance for future technical development. The total renewable electricity resource spans from about 70% to several times current generation. The non-electricity resource is relatively much smaller, with a large uncertainty wholly dominated by the potential for energy crops.

However the data are analysed it is clear that:

- Significant amounts of renewable energy can be economic *at current costs and prices*: the size of the economic resource depends upon financing assumptions, and could be much larger if traditional public sector criteria are used and/or energy prices rise for market or environmental reasons.
- A wide range of technologies needs to be considered. Wind energy is a major resource but by no means the only one.
- The total contribution of renewable sources could be very large especially for electricity production. Non-electricity contributions are relatively much more limited.

This seems to be a far cry from the view that renewable energy is necessarily marginal in future supplies. What about other countries?

Table 2. Estimated UK renewable energy resources.

Source	Resource (lower bound) Assumption	Electrical output (Twh/year)	Non-electric (mostly heat) (mtce/year)	Resource (higher bound) Assumption	Electrical output (Twh/year)	Non-electric (mostly heat) (mtce/year)
Large-scale hydro	Little additional potential owing to environmental objections	8		Extensive exploitation of remaining sites[a]	15	
Micro-hydro	Head >3 m Head <3 m All above 25 kW[b]	1.2 0.8		Smaller sites also exploited[c]	4	
Wind-onshore	Average 8 × 30 m turbines every 100 km^2	10		Average 25 × 60 m turbines every 100 km^2	200	
Wind-offshore	Min 5 km from coast Max 30 m depth Exclusion for fishing, seabed etc[d]	100		Deeper water accessible[d]	250	
Domestic and industrial wastes	20 Mt degradable @ 12 GJ/t, most landfill recovery 30%; electrical efficiency 30%	6	–	30 Mt degradable Half incineration: Half landfill:	18 2	7.5 –
Agricultural wastes[h]	20 Mt @ 14 GJ/t 50% recovered	11	5.0*	25 Mt 90% recovered	44	11.3*
Forestry[j]	5% land: waste collection @ 2t/Ha/year 5% land: rotation forestry @ 7t/Ha/year	2.3 8.4	1.0* 3.6*	10% land: waste collection @ 3t/Ha/yr: 15% land: rotation forestry @ 13t/Ha/yr:	10 82	2.6* 21*
Tidal	Severn and Mersey, Morecombe Bay and Solway Firth[k]	35		Extended schemes and improved performance[k]	50	
Geothermal hot dry rock (extracted over 100 years)	ETSU estimate of resource to 7 km depth at costs below 48 kwh (speculative)[n]	20		Guesstimate of potential over wider regions at higher cost cut off[o]	100	
Wave	30 MW/km × 500 km × 15% average efficiency	20		45 MW/km × 100 km × 35% efficiency	130	
Passive solar space heating[q]	15% contribution, in 40% building stock, 1987 heating levels		3.9	30% contribution in 60% of building stock, 50% more efficient		5.5
Active solar water heating[r]	40% contribution in 80% of building stock		5	60% contribution in 95% of building stock		30
Photovoltaics (PV, solar cells)	100 km^2 at 8% annual efficiency	9		750 km^2 at 12% annual efficiency	100	

Large-scale hydro, Almost all in Scotland. Current output about 6.3 TWh. Further use depends upon environmental constraints.
Micro-hydro, 90% of sites with >3 m head estimated to be economic at present.
Wind-onshore, UK wind resources strong; majority likely to be economic (see text).
Wind-offshore, Technology under development. Current cost estimates 3–9 p/kWh[e].
Domestic and industrial wastes, Current (1987) 20 Mt; most land fill extraction economic.[f] Incineration more efficient but maybe greater cost and environmental objections.[g]
Agricultural wastes, Current (1987) 25 Mt, about half straw, which is already used in a few industrial countries (eg Denmark) for heat. Gasification for gas turbines appears promising.[i]
Forestry, Current UK forest area 9% of land; EC average 22%. 'Crops' could include mixed deciduous species. Economics depend on conditions, could be favourable (see text).
Tidal, Economics heavily dependent upon financing assumptions. Debate over environmental impacts.
Geothermal hot dry rock, Technology under development; resource and economics still very uncertain (see text). Aquifer resources are very poor.[m]
Wave, Deep water, technology complex and little developed; wide differences of opinion about the economics and potential efficiency.[p] Shoreline resource cheaper but very small.
Passive solar space heating, Utilization limited by mismatch between solar input and heating demands. Economic potential probably greater in North because of the longer heating season.
Active solar water heating, Only special applications (eg swimming pools) economic at present.[r] Economics may improve for commercial/community sized heat distribution systems.
Photovoltaics, Central station use very constrained. Building surface/small scale mounting may be most attractive. Current UK roof area ~1 000 km^2. Large cost reductions needed (see text).

Notes:
[a]D. Birkett, 'Review of potential hydroelectric development in the Scottish Highlands', *Electronics and Power*, May 1979, pp 339–364; [b]Department of Energy, 'Renewable Energy in the UK: The Way Forward', *Energy paper No 55*, HMSO, June 1988; [c]M. Flood, *Solar Prospects*, Wildwood House, London, 1983 (Chapter 5); [d]A.P. Rockingham, R.H. Taylor and J.F. Walker, 'Offshore wind and wave power – a preliminary estimate of the resource', *Wind Energy Workshop*, Cranfield, 1981, Bedford BHRA; [e]Energy Technology Support Unit, 'Background relevant to the 1986 appraisal of UK energy research, development and demonstration', *ETSU R–43*, Department of Energy, HMSO, 1987; CEGB, private communication; [f]K.M. Richards, 'Landfill gas exploitation in the UK – an update', *ETSU L–25*, Energy Technology Support Unit, June 1988; [g]Rod Taylor, 'The true cost of landfill – energy recycling is a strong competitor', *Warmer Bulletin*, Summer 1989; [h]Estimates of agricultural waste volumes: Flood, *op cit* Ref c; Richards, *op cit* Ref f; J. Scurlock (private communication); [i]E.D. Larson, P. Svennignsson and I. Bjerle, 'Biomass gasification for gas turbine power generation', in Johannson *et al*, *op cit* Ref 45; [j]Data based on discussion with D.O. Hall, G.G. Bevan and G. Long, 'UK renewable energy programmes', *IEE Conference on Energy Options*, Reading, 1987, estimates a total biomass potential of up to 40 Mtce; [k]S.J. Wishart, 'A preliminary survey of tidal energy from five UK estuaries', *Proceedings 2nd International Symposium on Wave and Tidal Energy*, Cambridge, 1981 (BHRA, Cranfield); The most recent studies for the Severn have increased energy estimates by about 20% for the favoured line, to about 17 Wh/year (ICE Symposium on Tidal Power, November 1989); [l]Binnie & Partners, 'The UK potential for tidal energy from small estuaries', Energy technology Support Unit, *ETSU-5TP-4048 (P1)*, June 1987, revised October 1988; [m]Energy Technology Support Unit, *ETSU R–43, op cit*, [n]R.J. Taylor, 'The 1987/88 Geothermal HDR programme review', Energy Technology Support Unit, *ETSU R–46*, [o]Estimate loosely based on resource maps in R.A. Downing and D.A Gray, eds, 'Geothermal energy: the potential in the United Kingdom', *British Geological Survey*, HMSO 1986; [p]Energy Technology Support Unit, 'Prospects for the exploitation of renewable energy technologies in the United Kingdom', *ETSU R–30*, Department of Energy, 1986; D.A. Mollison, 'Wave climate and the wave power resource', in D.V. Evans and A.F. de O. Falcao, eds, *IUTAM Symposium on Hydrodynamics of Ocean Wave Utilization,* Springer-Verlag, Heidelberg, 1986; [q]Based upon figures in Energy Technology Support Unit, 'Resource Size Estimates for the Solar Heating Technologies', *ETSU Note N–5/81*, ETSU, November 1981; [r]*Ibid.* Solar water panels are widely used in the Mediterranean, but *ETSU R–43, op cit* Ref e, concludes that they would not be economic for domestic supply in the UK in any of the scenarios considered.

*Non-electricity figure is total energy content of recovered biomass, which could be used for various applications. Electricity figures show the total electricity potential of this (30% efficiency, lower limit; 50% efficiency, upper limit). Thus the heat and electricity figures cannot be added, though some heat recovery from generation would be possible.

Other countries

As noted, the UK's renewable resources are unusual. In few countries could the combination of wind and tidal (and wave if successfully developed) energy conceivably reach the contribution possible in the UK. In many industrial countries there is some further scope for hydro (micro hydro sites especially) but the potential is limited. Geothermal aquifer resources are small in most countries. Solar water heating and space heating are confined to those end-uses, and are limited further by the annual variations. Most countries have significant potential for using wastes, both industrial and agricultural; the practical resources on the basis of current technology are significant and in some cases already partially exploited,[44] but are limited compared with total primary requirements.

Drawing on the UK analysis, this suggests on a broad perspective that renewable energy could be significant on the basis of current technology, but that for it to be a major component of supply on a global scale, other technologies will be required. Three candidates stand out.

Photovoltaics (PV). Often known as solar cells, these convert sunlight to electricity at an efficiency far exceeding photosynthesis. Installed costs currently exceed the levels required for competing with baseload power generation even in the sunniest regions by a factor of 2–3. To become competitive on power systems the costs of cells need to come down further and the field efficiency must increase substantially to limit the 'balance of station' costs (eg mounting, interface with grid, etc).

The development of solar cells to date has not met some of the ambitious goals set in the 1970s but has nevertheless been impressive: in the decade 1978–88 commercial cell efficiencies increased by over 50% and costs reduced by a factor of at least five.[45] Many of those involved argue that the goals for grid competitiveness can be reached through a range of foreseeable developments in amorphous silicon cells within the next *five years*.[46] Of course, technical optimism is nothing new, but no-one disputes the fact that there are many clear possibilities for improvement, and that costs will fall substantially with larger-scale production. A recent research paper raises hopes of major further gains in efficiency beyond those currently forecast.[47]

If the goals are achieved, and/or there are large fossil fuel price rises, countries with both sun and space, such as the USA, North Africa, and many Asia–Pacific countries, can potentially generate as much renewable electricity as they can utilize and export within limits of the system.[48] It remains unclear whether building surface systems interfaced with the grid, which might offer a more acceptable way of realizing a large resource in more populous areas, will be practical, but prototype PV roofing tiles are already available and one extensive review concludes that 'development of the grid-connected PV roof market will probably occur in the mid-1990s'.[49]

Modernized biomass conversion. The many options currently available for converting various biomass resources to useful energy can prove viable given the right local conditions – availability of waste and local use for the energy – but they are limited. Simple wood stoves are around 10–15% efficient. Liquid fuels from fermentation or low temperature pyrolysis remain obstinately expensive, and the energy required for subsequent distillation is a substantial burden on efficiency. Producing gas from anaerobic digestion remains a slow and messy business, though it may be more promising on a large scale. Gas from high temperature pyrolysis is probably more promising, but the product is not suitable for domestic distribution and combustion.

All these processes are slowly improving. Also, the crop potential is uncertain, given the limited effort so far devoted to bio-energy crops when compared with the dramatic increase in food crop yields over the last half century. In addition there is a range of relatively new options for modernized biomass conversion. Thermal reduction using chemical catalysts, or use of modified organisms, may provide a better route to liquid fuels. Continuous engineering processes can in some applications replace batch processing, increasing throughput and reducing losses. New energy crops, including algae, can increase photosynthetic efficiency and/or exploit inhospitable environments. A recent US Department of Energy technology review concluded that 'Biomass as material for producing liquid fuel is reasonably capable of producing up to 13.9 quads [over 15% of US total primary energy requirement] and . . . would be used if oil and coal prices increase slightly, as they are expected to do'.[50]

Perhaps most striking of all is the potential for combining biomass gasification (through pyrolysis) with advanced gas turbine cycles. In principle this could result in the conversion of biomass to electricity with efficiencies over 40% – a dramatic step from heat or even liquid output at much lower efficiencies – with a relatively low cost technology.[51] The technical obstacles appear to be modest, and the potential is large. It has been estimated that with such a technology, Sweden could generate 25–40% of its current electricity consumption from its biomass and waste resources at a cost of around US$0.05/kWh.[52] Extracted minerals precipitate from the process and could be returned to the soil. Modernized biomass technology would enable tropical and temperate countries with sizeable forests, or with land available for suitable energy crops, to rely heavily on domestic biomass resources.

The third of the 'big three' infant renewable technologies is geothermal HDR. The idea of drilling holes into the ground to reach hot rock, fracturing it, and pumping water around to extract heat for electricity generation, seems absurdly simple. However, earlier optimistic assessments by the UK's Energy Technology Support Unit[53] have been revised following the failure to date to find a way of creating an effective fracture zone without excessive cost.[54] Possible options now may include: finding other ways of creating fracture zones; exploiting natural fracture zones; or finding ways to create much larger reservoirs than previously considered. In the absence of success in any of these, areas with very high heat gradients (eg in geothermally active regions) may still be attractive. Success in extending the technology to lesser heat gradients, such as those occurring in the UK, would mean that many countries even outside active regions could generate substantial amounts of electricity for decades or even centuries before the resources are depleted.

Markets and competing prices

If gasification for power generation is taken as the most promising technology for large scale biomass use, then all of these 'big three' infant renewable technologies produce electricity, as do wind and hydro. Electricity accounts for only about 15% of total energy end-uses in industrial countries, which equates to about 40% of primary energy, though this is growing. In most cases, even successful development of renewables could only meet a portion (albeit a large one) of this because of their variability and resource constraints. Solar might make large contributions to low grade heating in many areas, especially if combined with strong efficiency measures. But the 'problem within a problem' of fuels for transport and distributed heating, highlighted by IIASA a decade ago,[55] remains.

Biofuels could contribute if and when oil prices rise, but the indigenous potential in many countries is limited because of the fairly low conversion efficiencies combined with limits on suitable land. This should not obscure the fact that in terms of end-use energy, the biomass resource may be comparable with all the electricity-producing renewable resources combined excepting photovoltaics.

A possible larger scale link from renewables to the transport sector, and efficient heating, may be through hydrogen. The 'hydrogen economy' is not a new concept. A voluminous literature grew during the 1970s in response to concerns about oil resources. A major factor stimulating renewed interest in hydrogen, apart from environmental concerns, has been the publication of a recent report on obtaining hydrogen from solar cells in deserts by the World Resources Institute in Washington.[56] The report assesses the required technologies in detail and concludes that there are good prospects for this being competitive with other 'alternative' fuels, including the currently favoured methanol, though natural gas (CNG) cars are not included in the comparison partly on grounds of resource constraints.

There are undoubtedly major uncertainties concerning the economics and infrastructural requirements involved – it is only presented as a long-term option – but the concept is well beyond the realm of 'marrying one fantasy with another', as one critic complained. The implications of successful development would be large indeed, as it could mean a very large renewable energy resource[57] joining the international fuels market, though there is no suggestion that this would occur without a large rise in the price of transport fuels first.

Another possible link to transport could be through electric vehicles charged from PV, probably with a combination of cells on cars and recharging or battery exchange points at car parks.

What is the outlook for price competition? Renewable sources will be competing with conventional energies. It is implausible under almost any technical outlook that the costs of collecting and converting diffuse renewables can compete with the costs of drilling a hole in the ground and letting oil or gas well up. Yet this is not the primary issue. Even on an optimistic view of resources, oil can never again be priced down to a level at which it can dominate electricity markets for any sustained period; and if renewables penetrate transport it will not be due to competition at current oil prices, but either as a response to further price shocks from market and/or global environmental pressures, or as the winning candidate for environmentally acceptable substitutes in urban areas. Gas is more promising for electricity, but even this would probably face large price rises if it tried to dominate baseload supplies.

In most cases the main competitors in the electricity sector will thus be coal and nuclear. Coal is more expensive to extract than oil and gas, and the costs of use are being driven up by a range of environmental concerns – which include the sheer difficulty of building new stations and the possibility of a large carbon tax. Nuclear is far from guaranteed as a cheaper option, or indeed as an option at all in many countries. Partly for environmental reasons, there is also increasing pressure to remove existing subsidies in some countries which distort competing energy prices, and/or to offer deployment subsidies for renewables in lieu of environmental taxes on other sources.

Thus, quite apart from supplies for special cases and niche markets – which may in themselves be considerable – it is quite conceivable that as renewable technologies develop, bulk energy markets will be awaiting them. Conversely, however, the factors driving up competing prices will be less important if the use of fossil fuels is depressed. The more renewables (and efficiency) penetrate, the stiffer the economic hurdles will become, and this will be another factor setting limits on the likely scale of contributions.

Technical prospects: conclusions

The UK is unusual in that perhaps its largest renewable energy resource – wind energy – has recently passed adolescence, though it is far from fully matured. In many other countries assessments are more uncertain, and in particular, further technical development is required before any of the 'big three' infant technologies can make an impact on energy markets.

In itself this is no objection: any forecasts which neglect technical development will inevitably be wrong. It occurs continuously in all areas and RD&D funding of all technologies is based upon the expectation of technical development. This is especially true since the two main criteria upon which expectations for technology development can rest are fulfilled: potential avenues for major improvements have been identified, and expenditure to date has been wholly inadequate to test the engineering requirements for these proposals (few renewable technologies have received as much as one thousandth of the cumulative RD&D expenditure devoted to nuclear power).[58]

The prospects for a number of technologies, including at least two of the 'big three', appear to be much *more* favourable than did the prospects for wind energy a decade ago – for which assessments pointed to apparently overwhelming technical and other obstacles. Through accidents of circumstance and scale, wind energy developed very rapidly to the stage where it is being considered – and in some cases deployed – as a serious large-scale source. Given the right signals and support, the prospects for at least one and quite possibly two of the 'big three' infant renewables realizing their potential, together with many lesser but locally important resources, seem just as good.

The cursory analysis of resources and markets suggests that on technical and economic grounds it is almost impossible to construct all-renewable energy futures. But it seems relatively easy to visualize renewables making large contributions, especially if future world energy demand is constrained to levels not far above today's.

The timescales may not be long by energy standards. As noted, many significant technologies can already be commercial, or are merely awaiting price rises widely expected this decade. Photovoltaics and advanced biomass technologies, including gasification, could be well developed and into early stages of deployment by the end of the 1990s. Deployment will follow a traditional logistic curve, but one which could be speeded up by environmental concerns. Only the heavy engineering gothermal and offshore technologies are likely to take much longer to develop.

These conclusions focus primarily upon technical and economic considerations. There are of course other issues, including the current low profile and status of renewables, the relatively low level of industrial and government support, and the environmental impacts of renewables which could give rise to strong opposition. However, currently environmental concerns are one of the driving factors behind renewables and the idea that they will act to favour fossil and nuclear sources is difficult to sustain. All these issues are considered further in Part II: none of them, ultimately, invalidates the technical conclusions drawn above.

But returning to the present reality throws all this into sharp relief. Renewables other than hydro and traditional biomass are currently a minor factor in world energy supplies and their contribution in industrial countries is tiny. Most projections show them contributing at most a few percent even decades ahead. RD&D expenditure on the full and varied range of renewable technologies remains, in total, an order of magnitude less than expenditure on other energy sources, including much more speculative nuclear technologies. In considering the policy options to minimize carbon emissions, most of the first round country studies for the Intergovernmental Panel on Climate Change all but ignored renewables in their projections. In the hallowed halls of energy policy formation, renewables remain invisible. Why?

Part 2, Political and policy analysis, Chapter 19, examines the questions: why, and what can change.

This paper is an expanded version of a presentation given to the 4th RIIA/BIEE/IAEE Annual Conference, London, December 1989.

I am grateful to a number of people for providing thoughtful comments. I am indebted to James Cavanagh for redrawing Figure 5, and to Nicola Steen for preparing the other figures.

[1]World Commission on Environment and Development, *Our Common Future*, Oxford University Press, New York, USA, 1987.
[2]Direct government spending in IEA countries on all the renewable technologies in the decade to 1988 averaged under 10% of IEA government energy R&D, and has declined below this since the US-dominated peak of 1980–81 (Figure 1). This does not include indirect government or private expenditure. UK government R&D expenditure on renewables in 1985–86 appears to have been under 3% of total government supported energy R&D (ie including the nationalized industries and various nuclear agencies, Figure 2). This does not include tax concessions on private sector RD&D. Figures for private industry spending are not readily available but would probably reflect an even greater disparity.
[3]For example, the global International Atomic Energy Agency; the IEA's Nuclear Energy Agency; Europe's Euratom. A striking example of the absolute historical dominance of the nuclear vision can be found in the fact that nearly a fifth of the total text in the treaties forming the European Communities is devoted to the European Atomic Energy Community; there is hardly a paragraph on renewable energy.
[4]Commission of the European Communities, *The Internal Energy Market*, COM(88)238, makes no reference to the implications of the 1992 process for renewable energy industries or future development.
[5]HMSO, *Privatising Electricity*, CM322 February 1988. This made provision for a 'non-fossil' fuel quota, but this was defined in such a way as to suggest that nuclear power was assumed to be the only serious contender. A separate provision for a renewable energy quota was added later.
[6]Estimates of biomass use vary widely. This estimate is taken from J.M.O. Scurlock and D.O. Hall, 'The contribution of biomass to global energy use (1987)', *Biomass*, Vol 21, 1990, pp 75–81. The total is made up of an estimated 48 EJ (35% of supply) in developing countries, and 7 EJ (3% of supply) in developed countries.
[7]Estimated from *BP Statistical Review of World Energy*, BP, London, UK, 1989
[8]In Israel for example, 60% of homes rely primarily on solar panels for water heating; there is also high penetration in Greece.
[9]B. Sorenson, *Renewable Energy*, Academic Press, London, UK, 1979, gives a detailed technical analysis of renewable energy flows. J. Twidell and T. Weir, *Renewable Energy Resources*, E & F.N. Spon, London 1986, details the theory behind most renewable energy technologies.
[10]The World Energy Conference 1989 survey estimates a gross theoretical capability of over 25 000 TWh/year (90 EJ), of which about 10 000 TWh/year (36 EJ) is estimated as exploitable capability given current costs and conditions; (1989 Survey of Energy Resource, WEC, 1989).
[11]D.O. Hall, personal communication. The figure is more than double the 30 TW originally published in Twidell & Weir (ref 9) and revised data suggest a figure nearer 100 TW (P. Elliot, personal comm.)
[12]In theory, some solar-derivate resources can also be extracted at greater than the natural rate of dissipation, but this is not relevant in practice.
[13]Few areas have been surveyed for aquifer resources unless water breaches the surface in hot springs. The World Energy Survey of the 1978 World Energy Conference estimated a resource to 3 km depth of over 1 000 GW operating for 100 years. The 1989 survey stated '. . . 10 GW represents an ambitious but realistic target' (yielding about 0.1% of global energy). The economics would vary very widely, as would efficiency, with temperature and assumed maximum depth of exploitation.
[14]For a fuller and broader summary of renewable energy technologies see the International Energy Agency report *Renewable Sources of Energy*, OECD/IEA, March 1987.
[15]Most of the data refers to mainland Britain and immediate offshore regions.
[16]Fred Hoyle, *Energy or Extinction*, Heinemann Educational Books Ltd, 1977. The author assumed 17th Century technological performance.
[17]L. Bedford and D. Page, *The UK Department of Energy's Wind Energy Programme – a Progress Report*, EC Wind Energy Conference, Herning, June 1988.
[18]HMSO, *Renewable Energy in the UK: The Way Forward*, Energy Paper No 55, 1988.
[19]Electric Power Research Institute, *Cost Assessment for Large Wind Turbines*, EPRI AP-3276, Palo Alto, CA, USA, 1983.
[20]For a recent EC review of progress and costs see, H.N. Nacfaire and K. Diamantaras, *The EC's Demonstration Programme for Wind Energy and Community Energy Policy*, European Wind Energy Conference and Exhibition, Peter Peregrinus, Glasgow, Scotland 1989 and other papers in this volume.
[21]CEGB, Hinkley Point C power station public enquiry, *Proof of Evidence on Comparison of Non-Fossil Options*, CEGB 6. The 'best sites' are a very limited set of wind upland or coastal hill sites. As with nuclear, quoted costs have risen as the terms of finance have changed in the privatisation process; the perception of wind economics in other countries varies according to resources, criteria, electricity pricing and experience.
[22]The major recent US DOE technology assessment states that, in the context of the relatively poorer wind resources of the USA 'cost-effective and extremely competitive wind systems are attainable within the next five to ten years . . . high temperature power semiconductors can significantly "leap frog" . . . today's wind control systems', W. Fulkerson *et al*, *Energy Technology R&D: What Could Make a Difference?*, ORNL–6541, Vol 2, Supply technologies, Oak Ridge, TN, December 1990. Other developments expected include improved airfoils and structural dynamics.
[23]A.P. Rockingham, 'System economic theory for WECS', *Proceedings 2nd BWEA Wind Energy Workshop*, 1980; D.T. Swift-Hook, 'Firm power from the wind', *Proceedings 9th BWEA Conference*, Edinburgh, 1987; M.J. Grubb, 'The sensitivity of wind power economics to power system and wind energy characteristics', *Proceedings 10th BWEA Wind Energy Conference*, London, March 1988.
[24]E.D. Farmer *et al*, 'Economic and operational implications of a complex of wind driven generators on a power system', *IEE Proc A*, Vol 127, June 1988.
[25]The relationship for operating penalties is in fact convex, so that the simple linear rule-of-thumb tends to overstate penalties at lower penetrations, and underestimate them at higher penetrations, Grubb, *op cit*, Ref 23.
[26]These conclusions differ substantially from some earlier studies. For an extensive discussion see M.J. Grubb, 'The economic value of wind energy at higher power system penetrations: an analysis of models, sensitivities and assumptions', *Wind Engineering*, Vol 12, No 1, 1988
[27]H. Selzer, 'Potential for wind energy in the European Community: An assessment study', *Solar energy R&D in the EC*, Series G,

Vol 2, D. Reidel, Dordrecht/CEC (see comments on this estimate later). Total EUR-12 net electricity production in 1988 was 1 610 TWh, Eurostat statistics, 4B.

[28]M.J. Grubb, 'The economic prospects for wind energy on the British electricity system: a probabilistic analysis', *Proceedings 8th BWEA conference*, Cambridge, 1986.

[29]M.J. Grubb, 'A resource and siting analysis for wind energy in the UK', European Wind Energy Conference, Glasgow, June 1989. The underlying physical analysis of windspeeds has been challenged (CEGB, cross-examination at Public Enquiry into Hinkley Point C Reactor, October 1988) and as yet site measurements are in the author's view insufficient to determine empirically realistic resource profiles.

[30]For example, independent generators were charged local authority rates on the basis of plant capital value, which for wind energy resulted in a charge of about 1–1.5 p/kWh. The CEGB was subject to a different rating, at about a tenth of this. Privatization of the electricity industry may remove other obstacles to independent generation.

[31]E.L. Petersen, I. Troen and N. Mortensen, 'The European Wind Atlas', Riso National Laboratories, Denmark/CEC DGXII.

[32]Department of Energy, 'The Severn Barage Project: General Report', *Energy paper No 57*, HMSO, 1989.

[33]See notes to Table 2.

[34]Energy Technology Support Unit, 'Background papers relevant to the 1986 Appraisal of UK Energy R,D&D', *ETSU R–43*, HMSO, 1987.

[35]Denis Mollison, 'Wave climate and the wave power resource', in D.V. Evans and A.F. de O. Falcao eds, *IUTAM Symposium on Hydrodynamics of Ocean Wave Utilisation*, Springer-Verlag, Heidelberg, 1986.

[36]ETSU, *op cit*, Ref 34. It was recently recognised that some of the very high cost estimates for wave energy (above 10 p/kWh) arose from errors in estimating load factors (New Scientist, 14 April 1990, p. 22).

[37]R.A.W. Shock, 'An Economic Assessment of Hot Dry Rocks as an Energy Source for the UK', Energy Technology Support Unit, *ETSU-R-34*, 1986.

[38]ETSU/NORWEB, *Prospects for Renewable Energy in the NORWEB Area*, ETSU, 1989

[39]The summary study in fact estimated the wind resource by assuming that wind turbines could not be sited in a given square kilometre if that square contained any road or rail, or if it lay in a number of other designated areas, which seem rather severe criteria.

[40]Watt Committee, *Renewable Energy Sources*, forthcoming 1990.

[41]This diagram was in fact sketched by the author for the Watt Committee as an illustration of the principle of the cumulative resource-cost curve, and was adopted for the report on the grounds that no 'better' numbers existed.

[42]HMSO, *op cit*, Ref 18. Extensive summary tables of Departmental estimates are given in G.G. Bevan and G. Long, 'UK renewable energy programmes', 5th IEE Conference on Energy Options, Reading, UK, April 1987. The author developed table 2 largely independently of these estimates.

[43]The figures assume that all hydro and passive solar, 80% of the domestic and industrial waste figure, and half of that for agricultural wastes, wind and tidal (assuming a discount rate to reflect long term values) can be taken as 'confidently economic'.

[44]For example, the Scandinavian countries already use forest and municipal wastes extensively, including district heating schemes and conversion to ammonia fertilizer. Even in the USA, biomass is estimated to contribute about 4% of primary requirements, not far short of the nuclear contribution.

[45]D. Carlson, 'Low cost power from thin-film photovoltaics', in Johansson *et al*, eds, *Electricity*, Lund University Press, Lund, Sweden, 1989; R. Hill, 'Review of photovoltaics', in M.J. Grubb, ed, *Emerging Energy Technologies: Impacts and Policy Implications*, Gower, forthcoming 1991.

[46]*Ibid*. The US DoE five-year research plan targets, if achieved, would result in a cost of \$0.06/kWh in deserts and \$0.10/kWh in other Southern regions.

[47]K. Barnham and G. Duggan, 'A new approach to high-efficiency multi-bandgap solar cells', *Journal Applied Physics*, April 1990.

[48]Hill, *op cit*, Ref 45, states that, with suitable mounting strategies, the land area rendered unavilable for other uses with PV generation is comparable to that used by equivalent conventional sources (as with wind energy). The total area impacted, of course, would be very much larger, though less than that for wind energy.

[49]Carlson, *op cit*, Ref 45.

[50]W. Fulkerson *et al*, *op cit*, Ref 22, p 93. Estimates are based upon experience with coal gasification, which technically is much more difficult than gasifying biomass.

[51]E.D. Larson *et al*, 'Biomass gasification for gas turbine power generation', in Johansson *et al*, *op cit*, Ref 45. The technology which appears to offer the greatest advantages is biomass integrated gasification/intercooled steam injected gas turbines (BIG/ISTIG).

[52]The upper figure assumes 500 PJ of fuel input. Current wastes and forest residues amount to about 360 PJ, and it is estimated that a further 300 PJ could be obtained from short rotation forestry, *ibid*.

[53]R. Taylor, 'The 1987/88 geothermal HDR programme review', *ETSU R–46*, March 1988. An update of Shock, *op cit*, Ref 37, estimated that geothermal HDR might provide electricity at about 3.5p/kWh (1986 prices).

[54]ETSU, forthcoming. However, conversely, assessments from the US programme have become less pessimistic (T. Gray, private communication).

[55]W. Haefele *et al*, *Energy in a Finite World*, Ballinger, Cambridge, MA, USA, 1981.

[56]J. Ogden and R. Williams, *Solar Hydrogen: Moving Beyond Fossil Fuels*, World Resources Institute, Washington, 1989.

[57]It has been estimated that the equivalent of total US oil use could be produced from around 70 000 km^2 of PV collector field: 0.5% of US land area, or 7% of US desert area. *Ibid*.

[58]Detailed historical data are not available. Direct IEA government R&D expenditure on all the renewables has amounted to nearly 10% of energy R&D budgets since 1978. However, non-hydro renewable energy expenditure before 1974 was negligible in almost all countries. In many countries, nuclear R&D expenditure has maintained at current or higher levels for over 30 years. Setting this against the available data on recent public expenditures (as for Figures 1 and 2) suggests that with the possible exception of photovoltaics, few if any individual renewable technologies have received more than about 0.1% of the total public expenditure on thermal nuclear power R&D, even without discounting past contributions forward.

[59]Opinion poll data show consistent favourable attitudes towards renewable energy both in general and, in many cases, when focussed upon specific developments, though there have been notable exceptions particularly for hydro and some of the Californian wind areas. In Denmark, with the most developed renewable energy programme, attitudes have generally favoured wind farms developed by local enterprises but frequently opposed those by the utilities.

Chapter 2

Biomass Energy

D.O. Hall

Biomass provides about 14% of the world's energy, about 25 million barrels of oil equivalent per day (mboe/day) (=55EJ). It is the most important (35%) source of energy in developing countries but also plays a significant role in a number of industrial countries, eg the USA obtains 4% (1½ mboe/day) of its energy from biomass, and Sweden about 14%; both countries have plans to increase bioenergy production and use. Annual resources of biomass are eight times the world's energy-use but the problem is getting the energy to those who need it in an environmentally sustainable manner, and which is also economic when all internal and external costs are accounted for. There is considerable scope to modernize biomass energy production delivery systems to provide varied energy carriers such as electricity, liquid fuels and gases. Successful case studies for traditional and modern biofuels in a number of countries are presented. Economic, social and environmental issues are examined over the whole biomass energy spectrum.

Keywords: Biomass; Bioenergy; Environment

The world already derives a fifth of its energy from renewable resources – 14% from biomass and 6% from hydro (Figure 1). In the case of biomass this represents about 25 mboe/day (55EJ/year) and is the most important source of energy (35% of total) for the three-quarters of the world's population who live in developing countries.[1] Since the annual photosynthetic production of biomass is about eight times the world's total energy-use, and this energy can be produced and used in an environmentally sustainable manner, while emitting no net CO_2, there can be little doubt that this potential source of stored energy must be carefully considered in any discussion of present and future energy supplies. The fact that nearly 90% of the world's population will reside in developing countries by about 2050 probably implies that biomass energy will be with us forever unless there are drastic changes in the world energy trading patterns.[2]

Unfortunately, biomass energy has usually been relegated to the lowest priority, if considered at all, mainly because its primary use is in rural areas of developing countries where it often supplies over 90% of total energy requirements. Biomass is also a problem to planners and the like because it has diverse sources and end-uses and also interacts with land-use so resulting in many socioeconomic implications from production through to use. Nevertheless, biomass energy provision is being considered more favourably because of its role in the overall development process and because it is recognized that biomass can provide both traditional and modern energies such as electricity, liquid fuels and gases. This slow acceptance is being backed up by increased bioenergy-use in developed countries where, for example, the USA derives about 1.5 mboe/day and now has 9 000 MW of biomass electric power plants,[3] and Sweden, which derives 14% of its energy from biomass, has plans to increase this dramatically as it phases down nuclear and fossil fuel energies into the next century.

Although biomass energy-use is predominantly in the rural areas of developing countries, it also provides an important fuel source for the urban poor and for many rural small-to-medium-scale industries. We should thus address the issues of first, equity for the poor, and especially for women who are important actors in biomass energy provision and use through their cooking activities; second, environmentally sustainable land-use which requires that biomass in all its forms for food, fuel, etc, be sustainably produced; and, third, development and increased living standards which require increased energy provision. It is therefore imperative that we focus on the efficient production and use of biomass energy so that it can provide modern fuels such as electricity and liquid fuels, in addition to the more traditional, and very large role, as a heat supplier.[4]

The actual contribution of biomass to world energy supply will depend not only on the size of the resource base, but on a host of other economic and

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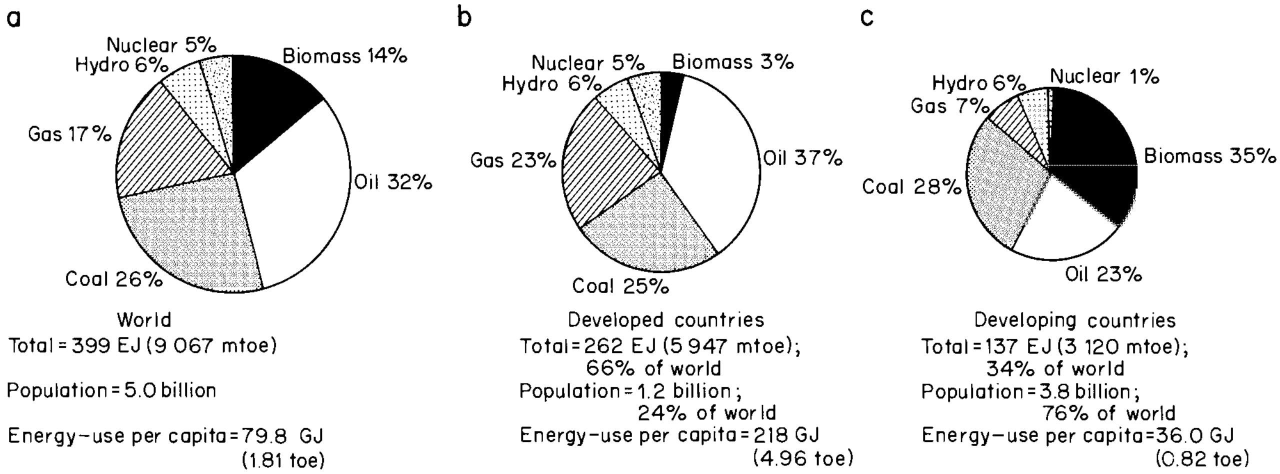

Figure 1. The contribution of biomass to global energy-use (1987).

Notes: 1.0 EJ = 10^{18}J (approximately equal to 1 Quad (USA), ie 10^{12} Btu); 1 mtoe = 44 × 10^6 GJ (44 × 10^{15} J) thus 1 toe = 44 GJ; 1 tonne/air-dry biomass (20% moisture) = 15 GJ; 1 tonne fuelwood = 1.4 m^3 wood; 1 tonne charcoal is derived from 6–12 tonne wood.
Source: Scurlock and Hall, *op cit*, Ref 1.

technical factors. A major factor will be the commitment by equipment manufacturers to develop advanced biomass power generating technologies, of which the gasification/gas turbine combination appears to be one of the most promising 'newer' technologies.

A new approach is required, centred on modern technology, to enable the full potential of this resource to be unlocked and contribute a greater market share in the energy consumption of any given country or region. Sustainable growth will not come about by chance, as resource allocation by the market may fail in areas such as the environment and the provision of public goods. Support is growing for a systematic approach in remedying certain shortcomings of the market mechanism, by attempting to make explicit – or internalize – the external costs of production and consumption.[5]

We can expect demand for biomass to rise considerably in the future, because of first, population growth, particularly in developing countries; second, greater use in the industrial countries due partly to environmental considerations; and, third, technologies presently being developed will allow either the production of new or improved biomass fuels, or the improved conversion of biofuels into more efficient energy carriers and thus stimulate demand for feedstock.

If these premises are accepted then we must examine carefully how biomass fuels have been produced and used in the past. This will allow us to draw on experiences in both developing and developed countries of successful and efficient practices which have resulted in sustained benefits at the local and national level.

As a result of an ongoing analysis of biomass energy projects around the world and detailed examination of four in India, Zimbabwe, Kenya and Brazil, we have concluded that the requirements for successful biomass projects depend mainly on the maximum participation and control by local people from the outset (including initiation and planning); they also need to receive short-term benefits within a longer-term context. Project implementation also needs to ensure sustainability, flexibility, and replicability as integral components – too great rigidity can be especially detrimental where economic benefits are difficult to calculate. The economics of these country examples and other similar examples need to be carefully analysed, even though they may be quite site specific, in order to determine whether any more general conclusions can be made.[6]

Can the data be trusted to reflect current knowledge? Can generalizations be drawn from such analysis? How replicable, how sustainable and how flexible are the examples, both nationally and internationally? These aspects of biomass will be discussed in detail later.

Biomass as an energy source has great opportunities and also problems. Its production and use, in an economic and sustainable manner, should be seen as an opportunity for entrepreneurs of all descriptions especially since biomass is so widely distributed and used throughout the world.

Biomass differs fundamentally from other forms of energy because of the diversity of types, production and use techniques in the overall energy production cycle, eg solid, liquid and gaseous fuels can be produced from dry and wet feedstocks. The cost of producing bioenergy thus differs considerably, and depends on many varying factors. There is no such thing as 'fixed' biomass production costs since the economics are quite site specific, especially if conversion technologies are excluded when making complete systems analyses.

Estimates of global distribution of energy-use are given in Figure 1 and in individual countries the use of biomass is shown in Tables 1 and 2. The single most important biomass energy source is fuelwood which in 1988 provided, according to the FAO, 457 mtoe. The Scurlock and Hall data[7] differ from official statistics which generally concentrate only on fuelwood and are also of dubious value but nevertheless are frequently cited in different forms without fully acknowledging their actual problematic origins.[8] No serious effort has been made in any country, to my knowledge, to place information on biomass energy production and use on an equal footing with more commercial and other fossil fuels, especially with regard to time series data. Thus the well known annual publication *BP Statistical Review of World Energy* does not list biomass energy for any country deliberately excluding it because 'fuels such as wood, peat and animal waste, which, though important in many countries, are unreliably documented in terms of consumption statistics'.[9]

Openshaw[10] summarizes well the problem with official statistics when he says 'it is known that production figures published by the FAO may be considerably underestimated because no accurate records are kept by many of the reporting countries of self-collected or self-produced products such as fuelwood, charcoal . . . Even the statistics for machine-sawn timber are unreliable owing to illegal felling practices in many countries'. Montalembert and Clement[11] of the FAO also illustrate this problem when they say that 'in national statistics, the fuelwood and charcoal production is assessed on the basis of the forestry data available, supplemented if necessary by estimates. But considerable amounts of fuelwood are also collected outside the actual forest lands, on uncultivated land or in rural areas, and are not accurately assessed. In many countries the data available are at best estimates or extrapolations based on partial consumption studies'. For example, the FAO estimate of worldwide wood consumption for 1976 was about 2.5 billion m^3 while Openshaw's estimate for the same year was about 4.8 billion m^3. The poor state of knowledge about fuelwood consumption and substitution patterns is confirmed by a World Bank report.[12] Having reliable information on biomass production and use is essential if resources are to be sustainably managed to provide both traditional and modern fuels, in parallel with fossil fuel markets which themselves have much stronger infrastructure and data bases.

It is also often not recognized, or documented, that biomass is used as an energy source not only for cooking in households, many institutions and service industries, but also for agro-industry processing and in the manufacture of bricks, tiles, cement, fertilizers, etc. These non-cooking uses can be substantial especially in and around towns and cities. Also, rural-based village and small-scale industries are frequently biomass-energy driven and play an important role in rural and national economies and are increasingly a focus of industrial development policies. Biomass energy is likely to remain the major source of heat energy for these industries for many years, since it is, at present, the only medium-to large-scale heat-energy resource which is economically viable and potentially sustainable. In India, for example, these industries account for as much as 50% of the manufacturing sector and provide a large part of national employment, second only to the agricultural sector.

The cost of importing energy can often be a substantial burden especially if a country's exports depend mainly on commodities. For example, Bangladesh, which derives about 90% of its energy from biomass only needed 7% of its export income in 1973 to import fossil fuels but this soared to 75% in 1981 and then decreased to 24% in 1988.[13] Since the Gulf crisis of 1990–91 petroleum costs in many countries have increased by 50% or more while commodity prices have declined. The reality of large import and export imbalances and energy insecurity are not passing phenomena, they have already been with us for 18 years.

The problem of devegetation in general, and deforestation more specifically, and its relationship to environmental degradation and global climate change, are important components of future biomass energy plans. The extent of net biospheric emissions of CO_2 to the atmosphere are hotly debated[14] but a 'most-likely' range is 1.5–3.0 Gt carbon/year.[15] This represents about 23 to 36% of total carbon emissions including fossil fuels. The use of biomass as a fuel is assumed to be on a sustainable basis in these overall calculations (no net CO_2 emissions) but this is certainly not always the case. Since the annual equivalent of about 1 300 million tonnes of oil is used in the form of biomass energy it will be important in balancing any country's carbon flows to

Table 1. Present biomass and commercial energy consumption patterns in selected developing countries.

Country	Population (1990) (millions)	Coal consumption 1988 (000toe)	Oil consumption 1988 (000toe)	Gas consumption 1988 (000toe)	Nuclear 1988 (mtoe)	Hydro 1988 (mtoe)	Total Commercial (10^9GJ)	Fuelwood -use FAO (10^6GJ)	Biomass -use BUN (10^6GJ)	Total energy consumption: FW+ Commercial (10^9GJ)	Total energy consumption: BIO Commercial (10^9GJ)	Present total (GJ/capita/year) (FAO)	Present total (GJ/capita/year) (BUN)	FW or BIO: % total energy consumption (FAO)	FW or BIO: % total energy consumption (BUN)
Developing countries (BUN)	3 420.0	598 896.3	397 431.0	59 879.5	8.7	60.4	47.3	14 089	35 695.2	61.36	82.96	18	24	23	43
Africa (BUN)	463.2	3 331.9	38 849.8	2 611.0	0.0	2.9	2.0	3 725	6 913.6	5.73	8.92	12	19	65	77
Botswana	1.3	300					0.01	13	25.8	0.03	0.04	20	30	51	67
Burundi	5.5	3	50			0.0	0.00	35	54.2	0.04	0.06	7	10	94	96
Egypt	54.1	728	14 550	2 117		0.5	0.75	22	379.5	0.77	1.13	14	21	3	34
Ethiopia	46.7		707			0.1	0.03	403	511.8	0.44	0.54	9	12	93	94
Gambia	0.9		61				0.00	10	9.0	0.01	0.01	14	13	79	78
Ghana	15.0	2	711			0.4	0.05	185	94.1	0.23	0.14	15	9	80	67
Kenya	25.1	70	1 694			0.2	0.08	376	403.7	0.46	0.49	18	19	82	83
Mauritius	1.1	49	334			0.0	0.02	0	14.4	0.02	0.03	15	28	1	47
Morocco	25.1	34	3 215	70		0.1	0.14	15	33.3	0.16	0.18	6	7	9	19
Mozambique	15.7	40	348				0.02	163	210.0	0.18	0.23	11	14	91	93
Nigeria	113.0	64	9 280	270		0.2	0.41	1 054	2 224.7	1.47	2.64	13	23	72	84
Rwanda	7.2		121	1		0.0	0.01	63	171.8	0.07	0.11	18	25	92	97
Senegal	7.4		600				0.03	40	43	0.07	0.07	9	10	57	59
Sierra Leone	4.2	0	198				0.01	42	42.9	0.05	0.05	12	12	83	84
Somalia	7.6		288				0.01	75	71.4	0.09	0.08	11	11	86	86
Sudan	25.2	0	1 446			0.0	0.06	202	843.0	0.26	0.91	10	36	76	93
Tanzania	27.3	2	514				0.02	326	925.5	0.35	0.95	13	35	94	98
Tunisia	8.2	80	2 341	153			0.11	32	52.8	0.14	0.16	17	20	23	33
Uganda	18.4		238				0.01	131	204.0	0.14	0.21	8	12	93	95
Zaire	36.0	204	824			0.4	0.06	343	361.5	0.40	0.42	11	12	85	85
Zambia	8.5	290	584			0.7	0.07	126	93.9	0.19	0.16	23	19	65	58
Zimbabwe	9.7	1 467	746			0.2	0.10	68	143.4	0.17	0.25	27	25	27	44
Central America (BUN)	128.5	1 360.9	73 786.3	14 104.7	0.0	2.8	3.9	444.0	750.8	4.31	4.62	34	36	10	16
Costa Rica	3.0		720			0.3	0.04	31	30.2	0.07	0.07	24	24	43	42
Dominican Rep	7.2	0	1 892			0.1	0.08	11	30.0	0.09	0.11	13	16	11	27
Guatemala	9.2		664			0.1	0.03	79	105.2	0.11	0.14	12	15	72	78
Haiti	6.5	0	915			0.1	0.04	58	51.5	0.10	0.09	10	14	84	82
Honduras	5.1	0	534				0.02	54	54.8	0.08	0.08	15	15	71	71
Jamaica	2.5	0	1 215			0.1	0.06	0	9.5	0.06	0.06	22	26	0	15
Mexico	88.6	1 358	66 600	14 104		2.2	3.54	160	405.0	3.70	3.94	42	45	4	10
Nicaragua	3.9		661			0.05	0.03	33	47.0	0.06	0.08	16	20	52	61
Panama	2.4	3	543	1			0.02	19	17.3	0.04	0.04	17	17	45	43
St Lucia	0.1		42				0.00	0	0.6	0.002	0.002	18	24	0	25

Table 1. Present biomass and commercial energy consumption patterns in selected developing countries ***(continued from page 714).***

Country	Population (1990) (millions)	Coal consumption 1988 (000toe)	Oil consumption 1988 (000toe)	Gas consumption 1988 (000toe)	Nuclear 1988 (mtoe)	Hydro 1988 (mtoe)	Total Commercial (10^9GJ)	Fuelwood -use FAO (10^6GJ)	Biomass -use BUN (10^6GJ)	Total energy consumption: FW+ Commercial (10^9GJ)	Total energy consumption: BIO Commercial (10^9GJ)	Present total (GJ/capita/year) (FAO)	Present total (GJ/capita/year) (BUN)	FW or BIO: % total energy consumption (FAO)	FW or BIO: % total energy consumption (BUN)
South America (BUN)	248.2	11 079.7	89 209.5	15 704.6	0.5	22.5	5.8	2 291.9	2 657.4	8.13	8.50	34	34	28	31
Argentina	32.3	323	16 634	11 707	0.5	1.4	1.28	47	86.3	1.33	1.37	41	42	4	6
Bolivia	7.3	0	892	226		0.1	0.05	14	107.7	0.07	0.16	9	22	21	68
Brazil	150.4	8 625	56 064	2 315	0.1	17.1	3.53	1 947	1 603.8	5.48	5.14	36	45	36	34
Colombia	31.8	2 031	8 881	994		2.5	0.61	167	523.5	0.77	1.13	24	36	22	46
Guyana	1.0	0	333				0.01	0	17.1	0.01	0.03	14	31	1	55
Peru	22.3	100	5 333	453		0.9	0.29	83	295.8	0.37	0.58	17	26	23	51
Uruguay	3.1	1	1 072	10		0.5	0.07	33	23.3	0.10	0.09	32	28	34	26
Asia (BUN)	2 597.4	583 112.8	195 429.4	27 459.2	8.1	32.2	35.5	7 627.6	25 597.4	43.17	61.14	18	24	18	42
Bangladesh	115.6	120	1 339	1 939			0.14	310	1 522.5	0.45	1.67	4	14	68	91
China	1 135.5	466 000	84 866	8 976	7.6	27.3	24.98	1 931	9 287.1	26.91	34.27	24	30	7	27
India	853.4	111 854	47 154	3 908	0.5	0.7	6.89	2 611	8 542.8	9.50	15.44	11	18	27	55
Indonesia	180.5	1 706	25 200	5 486		0.7	1.39	1 456	2 655.0	2.85	4.04	16	22	51	66
Malaysia	17.3	167	8 800	1 238		0.5	0.45	88	663.0	0.54	1.11	31	64	16	60
Nepal	19.1		181			0.0	0.01	183	440	0.19	0.45	10	24	95	98
Pakistan	122.7	1 917	7 672	5 850	1.0	1.4	0.71	244	1 245.9	0.96	1.96	8	16	26	64
Philippines	62.4	757	5 840	3		0.1	0.32	348	885.3	0.67	1.17	11	19	52	73
Sri Lanka	17.2	0	1 166			0.2	0.06	89	179.7	0.15	0.24	9	14	60	75
Thailand	55.7	593	13 211	59		0.3	0.60	368	206.1	0.96	0.80	17	14	38	26
Fiji	0.7	11	156			0.0	0.01	0	13.2	0.01	0.02	12	31	5	62
World	5 184.3	1 913 058	2 860 724	1 483 805	416	417	297.82	19 210		317.0		61		6	

Notes: [a] GJ = 10^9 J; [b] FW = fuelwood + charcoal only; [c] BIO = all biomass-use including residues; [d] cols 1–5 display fossil fuel and non-fossil commercial energy-use in 1988 and col 6 is the sum of these five cols, giving total commercial energy consumption for each selected developing country; [e] cols 7 and 8 show total biomass-use as estimated by the FAO and the Biomass Users Network (BUN). Whilst data for the BUN estimations encompass all biomass-use including residues, data for the FAO (UN) only estimate fuelwood and charcoal-use; and [f] cols 9 and 10 show total energy consumption including commercial (col 6) and biomass-use from FAO or BUN for direct comparison; [g] the data from cols 11 and 12 to calculate the total GJ/capita consumption figures shown; [h] the final two cols allow a comparison of the share of total energy consumption provided by biomass depending on whether FAO BUN data are used.

Sources: *BP Statistical Review of World Energy 1990*; UN Statistical Office, *Energy Balances and Electricity Profiles 1988*; UN Statistical Office, *Energy* Statistics Yearbook 1987; *FAO Forest Products Yearbook 1989*; OECD/IEA, *World Energy Statistics and Balances 1985–1989*; Biomass Users Network and Skills Centre, Kings College, London, UK.

Table 2. Present biomass and commercial energy consumption patterns in developed countries.

Country	Total commercial consumption (10^9 GJ)	Fuelwood -use FAO (10^6 GJ)	Biomass -use various (10^6 GJ)	Total energy consumption: FW+ commercial (10^9 GJ)	Total energy consumption: BIO+ commercial (10^9 GJ)	Present total GJ/Capita/year: FW only[a] FAO (GJ/capita)	Present total GJ/Capita/year: Biomass various (GJ/capita)	FW or BIO: % total energy consumption: FAO	FW or BIO: % total energy consumption: Various
Developed	235.85	2 925.8		238.8		215		1.2	
N America	92.01	1 338	4 022	93.4	96.0	339	348	1.4	4.2
Canada	10.33	74	540	10.4	10.9	393	410	0.7	5.0
USA	81.31	1 264	3 482	82.6	84.8	331	340	1.5	4.1
Europe	64.84	620	est[b] 1 050	65.5	est[b] 65.89	132	133	0.9	1.6
Albania	0.11	17		0.1		40		13.5	
Austria	1.12	15		1.1		151		1.3	
Belgium	1.80	6		2.2		210		0.3	
Bulgaria	0.76	19	17	0.8	0.8	86	86	2.4	2.2
Czechoslovakia	1.66	16	20	1.7	1.7	107	107	0.9	1.2
Denmark	0.60	4	88	0.6	0.7	119	136	0.7	10.4
Finland	1.00	32	150	1.0	1.2	207	231	3.1	13.0
France	8.28	112	336	8.4	8.6	149	153	1.3	3.9
Germany	14.61	47	101	14.7	14.7	190	191	0.3	0.7
Greece	0.92	22	42	0.9	1.0	94	96	2.3	4.4
Hungary	0.62	32	34	0.7	0.7	62	62	4.9	5.1
Iceland	0.07	0		0.1	0.7	224		0.0	
Ireland	0.37	0	46	0.4	0.4	100	112	0.1	11.1
Italy	6.38	48	162	6.4	6.5	112	114	0.8	2.5
Netherlands	3.12	1		3.1		211		0.04	
Norway	1.39	10	32	1.4	1.4	333	339	0.7	2.3
Poland	2.33	40	82	2.4	2.4	62	63	1.7	3.4
Portugal	0.50	6	34	0.5	0.5	50		1.3	6.3
Romania	2.11	49	45	2.2	2.2	93	92	2.3	2.1
Spain	3.49	36	38	3.5	3.5	90	90	1.0	1.1
Sweden	2.38	48	234	2.4	2.6	293	315	2.0	8.9
Switzerland	1.21	9		1.2		187		0.8	
UK	8.73	2	50	8.7	8.8	153	154	0.02	0.6
Yugoslavia	0.93	48	30	1.0	1.0	41	40	4.9	3.1
USSR	57.69	930	1 617	58.6	59.3	312	315	1.6	2.7
Asia	17.11	6		17.1		133		0.04	
Israel	0.21	0.1		0.2		45		0.1	
Japan	16.90	6		16.9		137		0.04	
Oceania	4.19	32		4.2		209		0.8	
Australia	3.52	31		3.5		212		0.9	
New Zealand	0.68	1		0.7		199		0.1	

Notes: [a] FW = fuelwood; [b] est = BUN estimate. *Assumptions*: 1 tonne of oil (toe) = 42 GJ; 1 GJ = 10^9 joules; Biomass/fuelwood = 15 GJ/tonne and air dry (20% moisture); Column 6 shows data gained independently from the FAO (UN); data from the Biomass Users Network (BUN) for selected countries; it should be noted that fuelwood in this Table is equivalent to the FAO's definition of fuelwood + charcoal only. Column 11 shows total commercial energy consumption including FAO fuelwood data.

Sources: UN, *Energy Balances and Electricity Profiles 1988*; UN, *Energy Statistics Yearbook 1987*; FAO, *Forest Products Yearbook 1989*; OECD, *World Energy Statistics and Balances 1985–1988*; BP, *Statistical Review of World Energy 1990*.

know the extent of biomass-use and regeneration.

In weighing energy options for the future we will increasingly factor in environmental aspects.[16] It is this favourable aspect of biomass energy compared to fossil and nuclear fuels, coupled with the ability to produce modern and traditional fuels in a decentralized manner, which makes bioenergy so important to analyse carefully. If we wish to go a step further to sequester CO_2 in biomass and then use the biomass as a substitute for fossil fuels there may be considerable economic and environmental benefits.

BIOMASS RESOURCES

It is relatively easy to obtain countrywide data (albeit imperfect) on standing biomass resources but annual yields are very difficult to obtain for natural vegetation, especially in developing countries. Since trees outside the forest also form the main source of biomass for most rural people we have an even greater problem trying to estimate sustainable yields.[17] Once we attempt to factor in access to biomass and site specific yields it becomes evident that generalizations on biomass availability are very difficult.

With these *caveats* in mind Tables 3 and 4 should be used only as a rough indication of the fuelwood and residue availabilities and the theoretical potential they may play in providing a country's energy needs based on varying yields and residue-use. More detailed analyses have been prepared for a recent study.[18] We aggregated energy-use (biomass and commercial) dependent on population and land area and calculated energy requirements based on the present developing country average (35GJ/capita) and twice this, but still only half the West Europe average of 140GJ/capita. The land areas required to provide 35GJ per capita at biomass yields of 2, 5 and 10 t/ha/year are then calculated. Thus Tanzania would have to use 13% of its land area at a yield of 5 t/ha to provide all its energy requirements from biomass, while Nepal would require 59% of its land. The yield scenarios span a median range but exclude tropical plantations which can attain 20–25 t/ha/year and exclude semi-arid regions where yields can be less than 1 t/ha/year.

Table 3 incorporates information of recoverable residues and also the areas of crop and forest lands. It shows that Tanzania, for example, could more than satisfy its present energy needs if it used 10% of its crop, forest and pasture land with yields of 5 t/ha/year; or if it used a quarter of its residues along with 5 t/ha yield on all its lands it would then need only 11% of its land area to satisfy its energy requirements.

Obviously these are theoretical calculations which gloss over the many country, regional and site specific problems of achieving such goals. They do, however, emphasize the potential which many countries have to provide a substantial proportion of their energy from biomass produced in a sustainable manner for both modern and traditional biofuels.

What these types of analyses miss is the issue of on-farm and village trees which are nearly all grown for multiple purposes, of which fuelwood is only one component – fodder, fruit, construction materials, shade, green manure, medicines, and income generation are other important benefits of trees. A recent study[19] of trees associated with a south Indian village (area 360 ha and 1 047 people) showed that there were 35 trees/ha with only 57 species evident. Fuel-only trees accounted for 4% of the trees, with twigs of all species being used as fuels. Interestingly the study showed that coconut plants are not counted as 'trees' and also that increasingly trees are being felled for sale to urban traders. This is a complex area of study but will become much more important as urban demands for fuelwood, charcoal and industries increase. How villages adjust to these new opportunities and problems in integrating agriculture and tree growing will be crucial to sustaining their environments.[20]

If biomass is to play a major role in the energy economy, strategies for sustaining yields over large areas and long periods are needed.[21] The experience of sustaining high sugar cane yields over centuries in the Caribbean and in countries like Brazil, suggests that this will be feasible, but good management practices and new research are required to achieve this goal.

Achieving sustainable production and maintaining biological diversity may require polycultural strategies, eg mixed species in various alternative systems can usually accommodate a variety of feedstocks. At present, however, monocultures are favoured for energy crops, in large part because management techniques in use today tend to be adapted from monocultural systems for agriculture. Polycultural management techniques warrant high priority in energy crop R&D.

The availability of high yielding clones should be seen as an excellent opportunity to improve yields overall and not as a problem of excessive uniformity. Much genetic diversity among tree species is presently available so that a mosaic of unrelated clones and mixed species is frequently the safest strategy for long-term sustainable yields. A poor strategy would be to use a mixture of only 2–3 clones. This should be combined with a re-examination of such practices as pollarding and more effort on optimizing coppicing practices since they markedly decrease land preparation and soil disturbances. In both arid and moist environments there are often distinct advantages to maintaining soil cover and/or water retention at certain times of the year, eg dry and monsoon seasons, and this will be reflected in long-term yields. Water management strategies have generally been neglected in the past but are crucial to plant production especially where irrigation is not practiced.

While net biomass energy yields for short rotation tree crops are typically 12 times energy inputs, it is desirable, both economically and environmentally,

Table 3. Potential for the use of existing biomass resources (land and residues) in selected BUN developing countries (1991).

Country	Population (1990) (millions)	Total land area (000ha)	Forests+ pasture croplands (Mha)	Residues energy content (10^6GJ)	Total energy consumption FW+ commercial (10^6GJ)	Present per capita energy-use (GJ/capita)	Total energy consumption if 35, 70 GJ/capita -10^6 GJ (35GJ/capita)	(70GJ/capita)	Land needed to supply 35 GJ/capita at 5 t/ha: Land needed (Mha)	% land area	+ 25% residues (Mha)	% land area	+ 50% residues (Mha)	% land area	5 t/ha 10% use forests + croplands pasture land (10^6GJ)	% total present energy consumption
Developing countries	3 798.5	7 645 094	5 019.8	56 198	86 702	23	132 949	265 898	1772.65	23	1585.12	21	1398.00	18	37 648	43
Africa (total)[a]	589.2	2 937 248	1 641.3	10 217	12 052	20	20 621	41 241	274.94	9	240.89	8	206.83	7	12 309	102
Botswana	1.2	56 673	46.3	55	26	21	42	84	0.56	1	0.37	1	0.19	0	348	1 357
Burundi	5.0	2 565	2.3	50	45	9	175	350	2.33	91	2.17	84	2.00	78	17	39
Egypt	49.1	99 545	2.6	316	1 017	21	1 720	3 440	22.93	23	21.88	22	20.82	21	20	2
Ethiopia	46.0	110 100	86.2	1 104	440	10	1 610	3 220	21.47	19	17.79	16	14.11	13	647	147
Gambia	0.7	1 000	0.4	15	12	18	23	47	0.31	31	0.26	26	0.21	21	3	27
Ghana	14.5	23 002	14.5	196	229	16	508	1 017	6.78	29	6.12	27	5.47	24	109	47
Kenya	22.4	56 969	9.8	595	443	20	784	1 563	10.45	18	8.47	15	6.48	11	73	17
Mauritius	1.1	185	0.2	61	17	15	38	76	0.51	274	0.30	164	0.10	54	1	8
Morocco	23.0	44 630	34.9	224	246	11	805	1 611	10.74	24	9.99	22	9.25	21	262	106
Mozambique	14.7	78 188	61.8	170	176	12	515	1 031	6.87	9	6.31	8	5.74	7	464	263
Nigeria	102.0	91 077	66.3	1 390	1 551	15	3 570	7 139	47.60	52	42.96	47	38.33	42	497	32
Rwanda	6.5	2 495	2.0	70	69	11	227	454	3.03	121	2.79	112	2.56	103	15	22
Senegal	6.8	19 253	30.9	113	68	10	238	476	3.17	16	2.79	15	2.41	13	232	340
Sierra Leone	3.7	7 162	6.1	43	39	10	131	262	1.75	24	1.60	22	1.46	20	46	118
Somalia	4.9	62 734	38.6	312	87	18	170	340	2.27	4	1.23	2	0.19	0	290	334
Sudan	22.8	237 600	115.0	781	245	11	779	1 598	10.65	4	8.05	3	5.45	2	862	352
Tanzania	24.2	88 604	82.5	580	352	15	847	1 693	11.29	13	9.35	11	7.42	8	619	176
Tunisia	7.4	15 536	8.4	76	178	24	259	518	3.45	22	3.20	21	2.49	19	63	36
Uganda	16.6	19 955	17.4	228	141	9	580	1 161	7.74	39	6.98	35	6.22	31	130	92
Zaire	31.8	226 729	197.8	354	405	13	1 113	2 226	14.84	7	13.66	6	12.48	6	1 484	367
Zambia	7.1	74 339	69.3	173	186	26	250	499	3.33	4	2.75	4	2.18	3	520	279
Zimbabwe	9.4	38 667	27.6	228	352	27	330	660	4.40	11	3.64	9	2.88	7	207	82
Central America[a] (total)	143.5	264 660	197.6	3 319	6 009	42	5 022	10 045	66.96	25	55.90	21	44.83	17	1 482	25
Costa Rica	2.7	5 106	4.5	103	72	26	96	191	1.28	25	0.93	18	0.59	11	34	47
Dominican Rep	6.5	4 832	4.2	130	93	14	229	457	3.05	63	2.61	54	2.18	45	31	34
Guatemala	8.4	10 843	7.2	185	121	14	295	590	3.94	36	3.32	31	2.70	25	54	45
Haiti	6.9	2 756	1.4	114	70	10	243	486	3.24	117	2.86	104	2.48	90	11	16
Honduras	4.7	11 189	7.7	131	77	17	163	326	2.17	19	1.74	16	1.30	12	58	76
Jamaica	2.4	1 083	0.7	29	79	33	84	169	1.12	104	1.03	95	0.93	86	5	6
Mexico	83.0	190 869	142.7	1 520	4 319	52	2 904	5 807	38.72	20	33.65	18	28.58	15	1 071	25
Nicaragua	3.5	11 875	10.2	98	62	18	123	245	1.63	14	1.31	11	0.98	8	76	122
Panama	2.3	7 559	5.8	63	50	22	80	159	1.06	14	0.85	11	0.64	8	44	87
St Lucia	0.1	61	0.0	2	2	18	4	7	0.05	77	0.04	68	0.04	59	0	12
South America[a] (total)	279.4	1 751 709	1 514.0	11 606	10 825	39	9 779	19 558	130.39	7	91.70	5	53.01	3	11 355	105
Argentina	31.5	273 669	237.6	1 456	1 772	56	1 103	2 205	14.70	5	9.85	4	4.99	2	1 782	101
Bolivia	6.7	108 439	85.9	180	73	11	236	471	3.14	3	2.54	2	1.94	2	644	886
Brazil	141.5	845 651	803.1	7 445	5 120	36	4 951	9 902	66.01	8	41.50	5	16.38	2	6 023	118
Colombia	29.9	103 870	96.3	863	900	30	1 048	2 096	13.97	13	11.10	11	8.22	8	723	80

continued on page 719

Table 3. Potential for the use of existing biomass resources (land and residues) in selected BUN developing countries (1991) *(continued from page 718).*

Country	Population (1990) (millions)	Total land area (000ha)	Forests+ pasture croplands (Mha)	Residues energy content (10^6GJ)	Total energy consumption FW+ commercial (10^6GJ)	Present per capita energy-use (GJ/capita)	Total energy consumption if 35, 70 GJ/capita -10^6 GJ (35GJ/capita)	(70GJ/capita)	Land needed to supply 35 GJ/capita at 5 t/ha: Land needed (Mha)	% land area	+ 25% residues (Mha)	% land area	+ 50% residues (Mha)	% land area	5 t/ha 10% use forests + croplands pasture land (10^6GJ)	% total present energy consumption
Guyana	1.0	19 685	18.1	36	14	14	35	69	0.46	2	0.34	2	0.22	1	136	956
Peru	20.7	128 000	99.7	285	427	21	725	1 451	9.67	8	8.72	7	7.77	6	748	175
Uruguay	3.1	17 481	15.5	295	97	32	107	214	1.43	8	0.44	3	−0.54	−3	116	120
Asia[a] (total)	2 780.4	2 637 420	1 662.1	30 918	57 648	21	87 314	194 627	1297.52	49	1194.45	45	1091.39	41	12 166	21
Bangladesh	106.7	13 017	11.8	960	514	5	3 733	7 466	49.77	382	46.57	358	43.37	333	89	17
China	1 085.0	932 641	532.8	9 179	26 579	24	37 975	75 951	506.34	54	475.74	51	445.14	48	3 996	15
India	786.3	297 319	248.1	10 075	8 916	11	27 521	55 041	366.94	123	333.36	112	299.77	101	1 861	21
Indonesia	172.5	181 157	146.5	2 314	2 844	16	6 037	12 075	80.50	44	72.78	40	65.07	36	1 098	39
Malaysia	16.3	32 855	24.2	433	701	43	569	1 138	7.59	23	6.14	19	4.70	14	182	26
Nepal	17.3	13 680	6.7	335	195	11	604	1 208	8.05	59	6.94	51	5.82	43	50	26
Pakistan	105.2	77 088	29.2	1 314	1 066	10	3 682	7 364	49.09	64	44.71	58	40.33	52	219	21
Philippines	57.1	29 817	19.9	525	805	14	1 997	3 994	26.63	89	24.88	83	23.13	78	150	19
Sri Lanka	16.7	6 463	4.1	157	151	9	585	1 171	7.81	121	7.28	113	6.76	105	31	20
Thailand	53.2	51 089	35.1	911	1 138	21	1 860	3 721	24.80	49	21.77	43	18.73	37	263	23
Oceania (total)	6.1	54 056	44.8	137	168	28	213	427	2.84	5	2.39	4	1.93	4	336	199
Fiji	0.8	1 827	1.5	35	9	11	26	53	0.35	19	0.23	13	0.11	6	11	129
World[a]	4 990.3	13 056 345	8 726.7	86 563	325 979	65	174 661	349 321	2328.81	18	1040.26	16	1751.72	13	65 720	20

Notes: Pasture: permanent pasture (FAO definition); FW = fuelwood + charcoal (FAO definition); croplands = arable + permanent cropland as defined by the FAO; Forests = forests + woodlands as defined by the FAO; [a]Africa, Central America, South Africa, Asia and world, are total data and not summation of BUN countries listed.

[b] Cols, 1–3 data comes solely from the FAO and excludes any water covered areas; [c] col, 4 shows total potentially recoverable residues energy content. This column is estimated from the three main sources of recoverable residues; forestry, agricultural and animal wastes. Data for forestry residues is calculated by assuming FAO round wood removals account for 50% of all cut wood and that of the remaining 50% abandoned on site 80% is recoverable. Agricultural residues are also calculated using FAO data for annual crop production from which is calculated the amount of recoverable residues, such as cereal straw, using coefficients from Hall and Overend, *op cit*, Ref 4. The same is true for animal wastes except a 25% recoverability factor is assumed and the dung production coefficients are from Taylor *et al*, Report No 113, Princetown University/CEES, Princetown, NJ, USA; [d] col 5, shows total energy consumption estimated from fossil fuel and 'renewable' energy-use, with renewables consisting of nuclear, hydro+geothermal and biomass. The data for biomass is from the FAO and is defined as fuelwood+charcoal use only; [e] col 6 present per capita energy-use is shown calculated for each country (see Table 3) and includes FAO estimates for fuelwood and charcoal use but not residues; [f] cols 7 and 8 shows country by country the total energy consumption if all countries consume the developing country average of 35GJ/capita (col 7) or a doubling of energy consumption (70GJ/capita col 8) as is predicted to occur in the next century. This is still only half the industrialized country average of 140 GJ/capita; [g] col 9 the area of land needed to supply 35GJ/capita if biomass productivities of 5 tonnes/ha/year (75GJ/ha) can be achieved. Col 10 shows this information in terms of the percentage of the country's total land area; [h] cols 11 and 13 also have a biomass productivity of 5 tonnes/ha/year, but in these cols it is assumed that residues are also used at either 25% or 50% ie 0.5 times the energy content of the recoverable residues (col 4) is able to be utilized. The changes in the percentage of total land area needed can be seen in cols 10 and 12 an 14; [i] col 15 calculates the amount of energy which could be produced if 10% of all forest, pasture and croplands where managed to grow biomass at 5 tonnes/ha/year; col 16 shows the percentage of total energy consumption (assuming 35GJ/capita consumption) this could potentially provide; [j] *FAO Production Yearbook*, FAO, Rome 1989; definitions for forest, crop pasture land: i) Forest = forest and woodland; land under natural or planted stands of trees, whether productive or not, and includes land from which forests have been cleared but that will be reforested in the forseeable future; ii) Cropland = arable + permanent crops; arable land is land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing pasture, land under market and kitchen gardens (including cultivation under glass), and land temporarily fallow or lying idle; permanent crops is land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee, and rubber; it includes land under shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber; iii) Pastures = permanent meadows and pastures; land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prarie or grazing land).

Table 4. The potential for the use of existing biomass resources (land and residues) in developed countries.

Developed countries	Population (1990) (millions)	Total land area (000 ha)	Forests and woodlands (000 ha)	Crop lands (000 ha)	Energy consumption FW+ commercial (10^9 GJ)	Residue energy content (10^9 GJ)	10 t/ha present energy consumption (mha)	% land	10 t/ha 2 present energy consumption (mha)	% land area	To supply present energy consumption at 10 t/ha/year: +25% of residential (mha)	% land area	+50% of residential (mha)	% land area	10% use for crop lands (10^9 GJ)	% total energy consumption
Developed	1 108.9	5 614 566	1 958 561	646 212	236.6	31.27	1 577	28	3 155	56	1 525	27	1 473	26	39 072	17
N America	275.7	1 838 757	732 389	236 016	93.0	11.95	620	34	1 240	67	600	33	580	32	14 526	16
Canada	26.5	922 097	436 400	46 101	10.4	2.29	69	8	139	15	66	7	62	7	7 238	70
USA	249.2	916 660	295 989	189 915	82.6	9.66	550	60	1 101	120	534	58	518	57	7 289	9
Europe	497.2	473 011	158 892	125 076	65.5	9.01	437	92	873	185	422	83	407	86	4 260	7
Alabania	3.2	2 740	1 280	713	0.1	0.05	1	31	2	62	1	28	1	25	30	23
Austria	7.5	8 273	3 754	1 516	1.1	0.23	8	91	15	182	7	87	7	82	79	7
Belgium-Lux	10.3	3 541	762	815	2.2	0.13	15	411	29	821	14	405	14	399	24	1
Bulgaria	9.0	11 055	3 728	4 133	0.8	0.19	5	47	10	94	5	44	5	41	118	15
Czechoslovakia	15.7	12 538	4 580	5 144	1.7	0.36	11	89	22	179	11	85	10	80	146	9
Denmark	5.1	4 237	484	2 606	0.6	0.14	4	96	8	192	4	90	4	85	46	8
Finland	5.0	30 461	23 225	2 404	1.0	0.48	7	23	14	45	6	20	5	17	384	37
France	56.2	55 010	15 075	19 232	8.4	1.26	56	102	112	203	54	98	52	94	515	6
Germany	77.1	34 952	10 192	12 419	13	1.16	88	250	175	501	86	245	84	239	339	3
Greece	10.0	13 085	5 754	3 940	0.9	0.16	6	48	12	95	6	46	6	44	145	16
Hungary	10.6	9 234	1 637	5 290	0.7	0.24	4	47	9	95	4	43	4	39	104	16
Ireland	0.3	10 025	100	8	0.1	0.00	0	4	1	9	0	4	0	4	2	2
Iceland	3.7	6 889	380	1 008	0.4	0.14	2	36	5	72	2	33	2	29	21	6
Italy	57.3	29 406	8 063	12 130	6.4	0.53	43	146	86	291	42	143	41	140	303	5
Netherlands	14.8	3 392	355	907	3.1	0.15	21	614	42	1 229	21	607	20	600	19	1
Norway	4.2	30 683	8 701	856	1.4	0.13	9	30	19	61	9	30	9	29	143	10
Poland	38.4	30 446	8 726	14 735	2.4	0.67	16	52	32	104	15	48	14	45	352	15
Portugal	10.3	9 195	2 976	2 757	0.5	0.16	3	37	7	74	3	34	3	31	86	17
Romania	23.3	23 034	6 675	10 649	2.2	0.68	14	62	29	125	13	58	12	53	260	12
Spain	39.3	49 944	10 811	20 420	3.5	0.52	24	47	47	94	23	45	22	44	468	13
Sweden	8.3	41 162	27 842	2 969	2.4	0.54	16	39	32	79	15	37	14	35	462	19
Switzerland	6.5	3 977	1 124	412	1.2	0.08	8	204	16	407	8	200	8	197	23	2
UK	56.9	24 160	2 178	7 031	8.7	0.59	58	241	116	482	57	237	56	233	138	2
Yugoslavia	23.8	25 540	10 490	7 774	1.0	0.42	7	26	13	51	6	23	5	20	274	28
USSR	188.0	2 227 300	928 600	232 473	56.8	7.95	379	17	758	34	366	16	352	16	17 416	31
Asia	128.0	39 714	25 390	5 166	17.1	0.61	114	287	228	574	113	285	112	282	458	3
Israel	5.0	2 062	110	433	0.2	0.02	1	65	3	129	1	62	1	62	8	4
Japan	123.5	37 652	25 280	4 733	16.9	0.59	113	299	225	599	112	297	111	294	450	3
Oceania	20.0	1 035 784	113 290	47 481	4.2	1.75	28	3	56	5	25	2	22	2	2 412	57
Australia	17.0	768 685	106 000	46 973	3.5	1.29	23	3	47	6	21	3	19	2	2 295	66
New Zealand	3.0	267 099	7 290	508	0.7	0.45	5	2	9	3	4	1	3	1	117	17

Notes: Land resources and energy-use (fuelwood+commercial and recoverable residues) are compared to provide scenarios for biomass supply at 10 t/ha/year productive.

to try to reduce energy inputs. For example, the nutrient status of afforested lands might be maintained by recycling nutrients and by choosing suitable mixed species and clones. The promise of such strategies is suggested by 10-year trials in Hawaii, where yields of 25 dry tonnes/ha/year have been achieved without N-fertilizer when Eucalyptus is interplanted with N_2-fixing Albizzia trees.[22]

Research can lead not only to improvements in present techniques for producing energy crops but also to new approaches. For example, long-term experiments in Sweden[23] have shown that: (1) in most forests trees grow at rates far below their natural potential; (2) nutrient availability is usually the most important limiting factor; and, (3) optimizing nutrient availability can result in four- to six-fold increases in yield. Under nutrient-optimized conditions all tree species investigated have behaved similarly to C_3 crop plants with about the same total biomass yield per unit of light intercepted by the leaves during the growing season. Growing trees under nutrient-optimized conditions thus makes it possible to achieve high yields with existing species and clones, so facilitating the incorporation of pest resistance and other desirable characteristics, and the maintenance of a diverse landscape mosaic. To the extent that croplands and wastelands would be converted to energy crops this way, it may be feasible not only to maintain but to improve biological diversity. An additional advantage of pursuing non-nutrient-limited production strategies is that the trees thus produced shift a percentage of their increased overall yield from roots to above-ground production, again similarly to the experience with agricultural crops.

Nutrient-induced yield increases can be achieved without nutrient leaching when good management is practiced. But achieving sustainable high yields this way requires implementation techniques being developed for matching nutrient applications to the time-varying need for nutrients. Thus, slow-release fertilizers are being used practically and in extensive trials in Japan and Sweden, for example.

CONVERSION AND END PRODUCTS

The great versatility of biomass as a feedstock is evident from the range of wet and dry materials which can be converted into various solid, liquid and gaseous fuels using biological and thermochemical conversion processes (Table 5). This makes it unique amongst carbon feedstocks. Details of these products and processes are given in numerous monographs and articles and will not be repeated here.[24] Examples of solid fuels are wood, charcoal, crop and forestry residues, agro-industrial and municipal wastes and briquettes. Biomass-derived liquids are mainly ethanol, some vegetable oils, and methanol (in theory only these days and not very much in practice). Gases are mainly biogas from anaerobic digesters, while now experiencing a rennaisance are gasifier-produced gases which can be used for electricity generation and possibly in the future coupled to efficient gas turbines which benefit from the favourable properties of biomass such as low sulphur and reactivity.[25]

Table 5. Biomass conversion product examples dependent on feedstock.

Feedstocks	Energy form Solid	Liquid	Gaseous
Wet	Briquette	Ethanol	Biogas
Dry	Fuelwood	Methanol	Producer gas

In the production and use of biomass the aim should be to optimize the productivities and energy efficiencies at all stages. It makes little sense to strive for high yields in the production, harvesting and storage phases if the conversion efficiency of the feedstock into a useful energy carrier is not optimal. Thus stoves and boilers, for example, should ideally be as efficient as practicable, the fermentation process to produce ethanol and biogas should be optimized, and efficient gas turbines should be used instead of steam combustion systems for the generation of electricity and/or heat. Thus we are advocating that the biomass energy system be made as efficient as possible from start to finish. This is obviously not novel but is very rarely done with biomass energy systems for many reasons which have to do with the historically poor status of biomass R,D&D and its neglect by planners and development agencies. Biomass energy systems have thus found it very difficult to adapt to changing socioeconomic and environmental pressures. Fortunately, this is now changing somewhat so there is an opportunity to use biomass efficiently for the production of modern energy carriers such as electricity and liquid fuels, and to improve the efficiencies associated with traditional biomass fuels such as wood and charcoal.

CASE STUDIES – SUCCESSES AND FAILURES

Since the recognition of the importance of biomass energy in the early 1970s, there have been many schemes and projects to help alleviate the shortages of biomass and to use wastes and residues and other biomass to provide biomass fuels of different types to rural and urban dwellers and to agriculture and industry, and in both developing and developed countries.

During this 20-year period there have been numerous proclamations of failure and success which need examination to determine whether general lessons can be learnt and then used in future implementation strategies. Failures have been attributed in the area of fuel-efficient stoves, biogas, gasifiers, rural electrification, fuelwood plantations, agroforestry, hydrocarbon plants, and doubtless others. Much of the criticism of such programmes has been warranted and has certainly helped focus attention on their shortcomings and previous uncritical acceptance.[26] In a number of instances such analyses have made recommendations for improvement which have benefited the further stages of development of these technologies.[27]

The designation of a successful project must be seen as relative to past failures and not imply that all is acceptable for any specific programme. Ideally a successful biomass programme should show *sustainability*, *replicability* and *flexibility* and also be economic when all costs and benefits are considered, especially externalities. The following list of 'successes' is probably contentious and each project can be criticized for a number of problems. Included in my personal list are the alcohol programmes in Brazil and Zimbabwe; electricity generation in California; straw-use and biogas in Denmark; landfill gas in the UK and USA; gasifiers in Finland, Mali and parts of India; stoves in Kenya; coconut residues in Sri Lanka; fuelwood in Nepal; eucalypts in Hawaii, Ethiopia and Brazil; willows in Sweden; agroforestry in Rwanda and Gujurat; bagasse in Mauritius; degraded land rehabilitation in Kenya; charcoal in Brazil; and municipal waste in Japan and Germany.

In evaluating biomass projects there are a number of generalizations which may be derived from past experience. They mainly evolve around the problem that biomass production requires land and time, that socioeconomic interactions with biomass production and use can be complex, and that it requires patience to understand biomass projects if sustainable and robust conclusions are to be drawn.

As a generalization I conclude that one should never believe any claims (written or verbal) pertaining to development projects whether they be biomass, agroforestry, forestry or whatever. There is ideally no shortcut to trying to understand the successes and failures of projects except by prolonged and repeated local visits and discussions over an extended period and interacting with diverse groups associated with a project. If this is not done conscientiously, and shortcuts to evaluation are undertaken, what is concluded about a particular project and the generalizations made therefrom can be biased and widely off-target.

From this author's own experiences and biases with biomass projects, the importance of early involvement by and benefits to the local people, the essentiality of flexible aims and optimum local control, a long-term approach, and multiple benefits, all stand out as being essential to success. If these key requirements are not recognized by donor and/or implementing agencies (and they very often are not) much money will be lost and much distress to the people and environment caused.

ECONOMICS

The following examples are taken from a large study[28] of 22 biomass energy projects in 12 developing countries but should not in any way be construed as representing all the possible data which is available. We also included some data on projects in five developed countries which may be of more general relevance. The detailed analysis of biomass energy availability and cost targets for the USA are especially interesting (Table 6) given the projected coal costs of $1.8/GJ in the next century.

The criteria for selection we have used were that as much economic data as possible was available in a disaggregated form and/or the projects had been operating for some years (the longer the better). As will be seen there are very few operating projects which fulfill both these requirements. Indeed the only operating technologies in specific cases which allow reasonably extensive analyses are ethanol, energy plantations, charcoal, biogas, and possibly gasification in developing countries, and in developed countries some programmes for producing ethanol, electricity from wastes and residues, short rotation forestry, and possibly biogas.

Three categories of technologies can be distinguished with differing economies. First, programmes which are presently commercial such as ethanol can be analysed in both developing and developed countries and some general conclusions can be drawn. These are the necessity for good yields, both in the production and conversion phases, and the necessity for considering all economic factors such as import substitution, energy security, subsidies, export poli-

Table 6. Potential biomass supplies for energy in the USA as estimated by the Oak Ridge National Laboratory.

Feedstock	Net raw biomass resources[a] (EJ/year)	Cost ($/GJ)[c] Current	Target
Residues			
Logging residues	0.8	> 3	< 2
Urban wood wastes and land clearing	1.2	2	2
Forest manufacturing residues	2.1	1	< 1
Environmentally collectible agricultural residues	2.0	1–2	1
Municipal solid waste and industrial food waste	2.4	2–3	< 1.5
Animal wastes	0.5	< 4	3.5
Subtotal	8.9		
Biomass from existing forest			
Commercial forest wood	4.5	< 2	< 2
Improved forest management	4.5		< 2
Shift 25% of wood industry to energy	0.5	2	2
Subtotal	9.5		
Biomass from energy crops			
Agricultural oil seed	0.3		
Wood energy crops	3.2	3	2
Herbaceous energy crops			
Lignocellulosics	5.5	4	2
New energy oil seed	0.4		
Aquatic energy crops			
Micro-Algae	0.3		
Macro-Algae	1.1	3.5	2
Subtotal	10.8		
Total	29.3[b]		

Notes: [a] These are biomass supplies net of estimated losses in production and handling, before conversion to fluid fuels or electricity.

Source: W. Fulkerson *et al*, *Energy Technology R&D: What Could Make a Difference? A Study by the Staff of the Oak Ridge National Laboratory, Vol 2, Supply Technology*, ORNL-6541/V2/P2, Oak Ridge National Laboratory, TN, USA, 1989, Table 2.4–3, p 85, December 1989; Hall, Mynick and Williams, *op cit*, Ref 21.

cy, etc; social and land-use policies must also be considered. Other technologies which fall into this first category of commercial viability are charcoal, electricity from wastes and residues, and possibly short rotation forestry (including fuelwood energy plantations in some instances). However, these technologies are not necessarily all sustainable in an environmental sense or viable without subsidies in certain forms.

A second category of technologies are those such as biogas, stoves, gasification and briquetting where demonstration and dissemination programmes have been underway for many years but they are not yet always sufficiently robust to operate commercially. They can be considered as being at the 'take off' stage but may not necessarily be successful either universally or in specific instances. Much will depend on local policies and on international energy factors.

The third category which has scarcely been analysed economically are projects such as those to rehabilitate degraded areas and/or to provide biomass in its various forms to local people. Examples are the various social forestry and agroforestry[29] projects such as the Baringo Fuel and Fodder project[30] and the Nepalese Community Forestry Programme[31] which are definitely not economically viable when considered by conventional criteria, even though they may have been operating for many years. The problems associated with such projects are legion and cannot be considered in this analysis even though they are crucial to many parts of the world.

How do you pass from categories three to two and from two to one? The most complex is with the third category where socioeconomic and land-use problems are diffuse while also being of overriding importance. Long-term funding is essential if any success is possible which will allow the techniques and technologies of project implementation to be sustainable and also to encourage replicability. Conventional economic paybacks are usually very tenuous so making it difficult to progress to the second category where economic criteria become much more important.

In the second category there start to be chances for entrepreneurs to operate and for costs to decline in relation to technical improvements. Thus stoves can be improved, their costs reduced and marketing improved. Biogas digesters can be constructed with designs for lower cost and easier maintenance and an infrastructure for technicians and builders established. Such technologies still usually require some form of subsidies and/or aid but the social costs and benefits are much more clearly seen compared to category three. The policy and institutional changes required for wider dissemination are also more clearly discerned and thus decisions are more easily taken and maintained.

The first category which includes ethanol, electricity and others, is far easier to analyse, albeit the conclusions of such analyses are frequently hotly debated, eg the Brazilian alcohol programme.[32] Generally the debate revolves around the extent of subsidy (if it exists) which is required to make these biomass energy systems economically viable in the conventional sense. If 'externalities' such as employment, import substitution, energy security, environment and so on, are also considered then the economics change usually in favour of the biomass systems. The technologies used in this category are often universally available so that technology transfer to optimize production and conversion can be quite easy – given the appropriate institutional structure and financial incentives, especially in comparison with fossil fuels. Indeed, a number of developing countries could relatively easily adapt and improve the technologies for these so-called modern biofuels, eg efficient ethanol distillation plants with low effluents, and biomass gasifiers plus turbines for electricity.[33]

Thus, we can conclude that the options for producing and using biomass as a source of energy are numerous. The problems generally lie in the ability to have good productivities on a sustainable basis to provide energy and other benefits which are desirable from economic, social and environmental viewpoints. Generalizations are difficult and can only be derived from individual case studies which have been carefully analysed over long time periods.

Ethiopia: eucalyptus plantations

Ethiopia is one of the least developed countries in the world. The country's main potential lies in agriculture which represents 40% of GDP, 90% of exports and 85% of total employment. About 94% of the land under cultivation is operated by individual farmers with landholdings averaging two hectares or less. The agricultural population is concentrated in the high-rainfall highland areas which are subjected to serious soil erosion. Forest cover is now reduced to 3% of the country.

Ethiopia has a long tradition and experience in plantation forestry, dating back to the end of the 19th century. The existence of Addis Ababa as a capital was threatened by a developing fuel shortage, due to overcutting of natural forests. As a potential solution, eucalyptus were introduced into the country in 1895. The introduction was a success and early in the 20th century plantations of eucalyptus for fuel were initiated on a large scale. The farmers around Addis Ababa adopted the new species for fuelwood and started planting their own woodlots, and also larger plantations. For almost 100 years small-sized eucalyptus wood has been highly appreciated by rural and urban dwellers both as a fuel and as light-scale construction poles.

The fuelwood plantation forestry around Addis Ababa, as well as around almost every major Ethiopian city, developed steadily until the 1970s. Plantations, mainly with *Eucalyptus globulus*, were established on more than 100 000 ha (15 000 ha around Addis Ababa). Approx 20 000 ha are planted annually compared with an estimated nationwide deforestation rate of 200 000 ha. The total plantation area in Ethiopia was about 310 000 ha in 1985.[34]

Establishment of additional plantations with the main emphasis on fuelwood began to be considered during the energy crisis of the 1970s. In Ethiopia the biomass fuels are mainly fuelwood, charcoal, cow dung and crop residues. The annual amount of wood harvested for household fuels totals 18.8 Mm^3. In sustainable forestry this amount of wood corresponds to about 1 M ha of well-managed, productive eucalyptus plantations, or alternatively about 5 M ha of indigenous forests. Recognizing the worsening fuelwood shortage, the government announced a reforestation programme in the Ten-Year Plan (from 1985 to 1995) which called for 2.9 M ha of land to be planted for fuelwood, especially *Eucalyptus globulus*.[35]

The ultimate goal of energy plantations in Ethiopia is to substitute all the currently burned cow dung and crop residues, about 3.5 mtoe and 2.5 mtoe respectively, with fuelwood. This required an additional 24.7 Mm^3 of wood; if all cow dung and crop residues were to be replaced by fuelwood, the annual demand for fuelwood will increase to about 45.5 Mm^3 annually. The area required for new plantations is about 3 M ha. Taking into account the population growth rate of 2.9%, based on a total population of 42 M in 1985, the overall demand for fuelwood will rise by the year 2000 to 66.8 Mm^3/year. The required plantation area would be around 4.5 M ha, assuming the fuel consumption rate does not change. In addition, about 1.2 Mm^3 of wood is consumed annually by the industrial sector.

Pohjonen and Pukkala[36] have analysed the cost of Eucalyptus plantations in the central Highlands. Their economic analysis is based on computer simulations which covered a seedling rotation and three successive coppice rotations. Calculations were carried out for four site productivity classes of plantations. The rotation length that maximizes the land expectation value is 12 to 20 years for seedling rotation and 8 to 16 years for coppice rotations with discount rates between 2 to 8%. The mean wood production is over 40 m^3/ha/year in the best site class and about 10 m^3/ha/year in the poorest class, with rotation lengths ranging from 10 to over 20 years. The internal rate of return (IRR) is between 18 to 20%, which well justifies the production of fuelwood from Eucalyptus in Ethiopia.

Brazil: charcoal

Charcoal production falls into three main categories: 1) subsistence producers who only market charcoal to acquire cash; economics and cost control are generally of little interest to this group. In many countries subsistence-produced charcoal is a major part of total charcoal production; 2) this group produce and sell charcoal as a business in which the circulation and growth of the capital invested in the business is their main concern; and, 3) the production of charcoal on a large scale for industrial purposes for example in Brazil for the steel industries.

To set up a medium- or large-scale commercial charcoal project requires a team of professionals who must cover the fields of forestry, engineering, technology of the production process, economics and marketing. Commercial production of charcoal is thus a complex task. There are numerous studies of charcoal conversion efficiencies and costs.

Brazil is the world's largest producer of charcoal with about 44.8 Mm^3 (11.6 mtoe) in 1989. The main producer is the state of Minas Gerais with about 30.3 Mm^3 followed by São Paulo and Rio de Janeiro with 1.9 M and 1.6 Mm^3, respectively. Charcoal is mainly used in the pig iron and steel industries which consumed 7.1 mtoe of charcoal in 1989. The charcoal industry employed over 267 000 people in 1989 and generated about $5 billion.[37]

Due to the particular combination of natural resources available in Brazil, particularly in Minas Gerais, charcoal-fired iron and steel production has been profitable, and is likely to remain attractive as long as wood is available and some kind of government incentives remain.

Charcoal production from 1979 to 1988 increased nearly twofold from natural forests and nearly fourfold from plantations. Tax credits for industries which invest in reforestation, and the legal requirement that companies using fuelwood must develop plantation areas, have resulted in extensive planting; more than 1.9 M ha has been replanted in Minas Gerais alone in the past 20 years. However, many of the early plantations were initiated by industries solely in order to gain tax benefits or to comply with reforestation laws with the result that they were poorly managed in many instances and have yields of less than 15 tonnes/ha/year. More recent plantations which are better managed can produce 15–30 tonnes/ha/year, or even higher yields.

If plans for Brazil's Grande Carajas Programme in Amazonia go ahead, an additional 2.3 to 3.0 Mt of charcoal would be needed for the pig-iron plants and could potentially cause serious ecological problems. Anderson[38] estimates that the charcoal-consuming industries in the eastern Brazilian Amazon (now being established or planned) would require over 14 Mt of fuelwood which will be supplied primarily by native forests. Because the prospects for sustained management are considered unlikely, Anderson calculates that over 1 500 km^2 of forest land could be destroyed for fuelwood production annually, thus exacerbating regional deforestation and environmental degradation.

To meet Brazil's industrial demand for charcoal up to the year 2000, would require an additional 287 000 to 353 000 ha/year planted at an estimated cost of between $2.8 to 3.4 billion. Charcoal demand in Minas Gerais alone will increase to about 8 Mt in 2005. This growing demand for charcoal exceeds the sustainable yields of local forests, and could create substantial wood shortfalls. The result of such a scenario could be widespread deforestation and the collapse of the state's charcoal-using industries. If projected demand is to be met, this would require roughly doubling the planted area in the next decade which may lie be either socially or economically feasible. Thus a solution may lie in the combination of demand reduction for fuelwood, increase in kiln efficiency, and wood supply increases. Production of charcoal has mushroomed without a significant improvement in average efficiency of wood conversion to charcoal. The traditional kiln, which accounts for about 80% of charcoal production in Minas Gerais, has an energy efficiency of 49% (ratio of energy content of charcoal output to energy content of wood input).

Campos and Toninello[39] have carried out an analysis on the financial and economic feasibility of charcoal production from forest plantations. At charcoal market prices of $120/tonne, plantations with a productivity under 18 m^3 ha/year and with transportation costs over 300 km from consumer centres, would be uneconomic. (In 1989 prices were about $94/toe.)

Mauritius: bagasse residues

Agricultural residues in certain regions have a large potential for energy production but this potential is currently under-utilized in many areas of the world.[40] In wood-scarce areas, such as China, the northern plains of India, Bangladesh and Pakistan, agricultural residues are often the major cooking fuels for rural households. In these areas as much as 90% of household energy in many villages comes from agricultural residues. It has been estimated that about 800 million people worldwide rely on agricultural residues and dung. Sugarcane residues (bagasse and tops plus leaves – called barbojo), are particularly important and offer an enormous potential for generation of electricity.[41] Contrary to the general belief, the use of animal manure as an energy source is not confined to developing countries alone, eg in California a commercial plant generates about 17.5 MW of electricity from cattle manure and in the EEC a number of plants are operating. The 9 000 MW of biomass electricity in the USA is mostly agriculture and forestry residues.

Among the advanced technologies for modernizing bioenergy that could be commercialized in the near term, biomass integrated gasifier/gas turbine (BIG/GT) technologies for cogeneration or stand-alone power applications have the promise of being able to produce electricity at lower cost in many instances than most alternatives.[42] For developing countries, the sugarcane industries that produce sugar and fuel ethanol are promising targets for near term-applications of BIG/GT technologies.

Depending on the choice of the gas turbine technology and the extent to which barbojo can be used, the amount of electricity that can be produced from cane residues could be up to 44 times the on-site needs of the sugar factory or alcohol distillery. Revenues from the sale of electricity co-produced with sugar could be comparable to sugar revenues, or alternatively revenues from the sale of electricity coproduced with ethanol could be much greater than the alcohol revenues. In the latter instance, electricity would become the primary product of sugarcane, and alcohol the by-product.[43]

Globally, an estimated 50 000 MW of BIG/GT capacity could be supported using for fuel the sugarcane processing residues that are currently produced.[44] The potential of electricity production from sugarcane residues in the 80 sugarcane producing developing countries could be up to 2 800 TWh/year, which is about 70% more than the total electricity production of these countries from all sources in 1987. In India, for example, electricity production from sugarcane residues in 40 years time could theoretically be up to 550 TWh/year; for comparison, total electricity production from all sources in 1987 was less than 220 TWh.

This lengthy introduction serves to put the Mauritius bagasse to electricity plant into perspective and show how this decade-long operating experience is relevant to programmes now being proposed for electricity plus alcohol production on sugar estates in many parts of the world.

The economy of Mauritius is dominated by the production of sugar, which still occupies around 88% of the cultivateable area. Bagasse is playing an increasing role in power supply and currently provides around 10% of Mauritius's electricity requirements. Woody biomass supplied approximately 63% of all the energy required for household cooking in the country – 3.5 (10^6) GJ in 1988. There is a potential for producing 10.2 10^6 GJ, using the by-products of the sugar industry.[45]

The Flacq United Estate Limited (FUEL) is the largest sugar estate in Mauritius with an annual average production of 0.7 Mt of fresh cane, and 79 000 tonnes of sugar. FUEL was among the first sugar estates to produce excess steam for production of electricity for sale to the national grid in the mid-1950s. In 1982, the FUEL sugar estate installed a dual fuel, bagasse and coal furnace to produce electricity all year around and substantially increase its output. A boiler with capacity of 110 t/h, 42 bars pressure and a condensing turbine coupled with a generator of 21.7 MW led to an average production of 75 $\times$ 10^6 kWh of excess electricity (30 $\times$ 10^6 kWh produced solely from bagasse during the crop season and 45 $\times$ 10^6 kWh from coal); this represents around 12–15% of the total electricity requirements of Mauritius.

In 1989 the electricity export by FUEL increased to 94×10^6 kWh (26×10^6 from bagasse and 68×10^6 from coal) representing about 16% of the country's total requirements. In addition the estate consumed 12×10^6 kWh itself. Details of economic costs are not yet available following the installation of an updated plant and negotiations with the electricity board.

China: biogas

Biogas has the potential for multiple uses eg cooking, lighting, electricity generation, running pumpsets and other agricultural machinery, internal combustion engines for motive power, etc. However, the technology of anaerobic digestion has not yet realized its promised potential for energy production. This is despite the fact that it could be considered one of the most mature biomass technologies in terms of the numbers of installations and years of use. In industrialized nations biogas programmes are often hindered by operational difficulties, a lack of basic understanding of the fundamentals involved, and little engineering innovation. In some developing countries, development of biogas programmes has lacked urgency because of readily available and inexpensive noncommercial fuels such as fuelwood and residues. Lack of local skills can also be a significant deterrent to optimization and widespread acceptance of biogas technology, together with costs, even though the advantages of waste treatment are widely recognized.

For over 50 years the Chinese have struggled to develop and diffuse biogas technology. At present, China has about five million household digesters in working order. Although over seven million have been constructed in the past many of them were poorly built mainly because during the 1950s and 1970s quality was sacrificed at the expense of quantity. Today about 25 million Chinese people use biogas mainly for cooking and lighting. A further 10 000 large- and medium-size biogas digesters are working in food factories, wineries, livestock farms, etc. Biogas produced in large enterprises is transferred to centralized biogas supply stations, biogas motive power stations (there are 422 such stations with a installed capacity of 5 849 hp) or biogas electric power stations (there are 822 such stations with a total of 7 836 kW). An important characteristic of the Chinese biogas programme is that in addition to animal and human dung a major feedstock is straw of which about 2 Mt is digested each year.[46]

Daxiong *et al* published an economic analysis of 58 biogas plants in Tongliang (Sichuan) and compared this with data produced by other researchers in 242 biogas plants in Hubei. Their analysis shows a high rate of return on investment in biogas and short payback periods of between one and four years. Capital costs vary from 15 to 40 yuan per m^3 of digester capacity, and the annual gas output varies from about 30 to 40 m^3/year for each m^3 of digester. The annual value of this biogas in terms of savings in coal, kerosene, burned biomass, labour and fertilizer varies from about 7 to 16 yuan (Renminbi foreign currency units = 371.28 yuan, 20 January 1987). If operating costs are included, the internal rate of return (IRR) varies from 59% to 114%.

Biogas plants in China have been subsidized or received low interest loans. Since 1980 the state has allocated more than 10 million yuan every year for the development of biogas, which represents 200 yuan for each plant constructed every year. This money is spent in improving biogas equipment, promotion, standardization, servicing, training, research on new technology, etc.

Since 1983 there has been a move toward financial self-reliance which has resulted in a reduction in subsidies from two-thirds to one-third. This has led to a decrease in the construction of biodigesters. Although the rate of return remains high, the increase in the initial outlay is a disincentive to users.

Socioeconomic changes in China are also affecting biogas production. Labour is often not available and a growing number of peasants prefer to buy privately sold coal than to use biogas, because they believe they save valuable time which they can spend on more lucrative work.

This changing situation seems to indicate that production and management of biogas will become more centralized and industrialized for both rural and urban areas and that it will be used as part of an integrated production system. In this way, advanced technology could be used to increase production and financial returns and thus will have greater appeal to peasants. Energy shortages thus may be one of the fundamental motives for the continued development of biogas.

Brazil: ethanol

Global interest in ethanol fuels has increased considerably over the last decade despite the fall in oil prices after 1981. A number of countries have pioneered both large- and small-scale ethanol fuel programmes. Worldwide fermentation capacity for fuel ethanol has increased eightfold since 1977 to about 20 billion litres/year in 1989. Bioethanol fuel is produced on a large scale in Brazil and the USA.[47]

The current USA fuel ethanol production capacity is over 4.6 billion litres and there are plans to increase this capacity by more than 2.3 billion litres. However, doubts remain as to the future direction of this industry due to the controversy regarding costs.[48] Highly variable maize and byproduct prices and the wide variations in final ethanol costs among existing plants over time highlight the non-subsidy aspects of the costs controversy. For example, from 1980 to 1987 maize prices have varied from $1.41 to $3.16 bushel, while byproduct sales recouped as little as 30% of maize costs for dry milling to 90% of the cost of maize for wet milling. The calculated full cost of production from stand-alone plants has ranged from as low as $0.19/litre to about $0.38/litre from 1980 to 1987. Ethanol is cost competitive as a fuel blending agent with existing Federal excise tax exemption, with maize costs of $2.00/bushel, and with byproduct recovery of 50% of the cost of maize, if oil prices are $20/bbl or more. Without the Federal subsidy, crude oil prices must be at least $40/bbl for ethanol to be competitive according to LeBlanc *et al.*[49]

Brazil has the world's largest bioethanol programme. Since the creation of the National Alcohol Programme (ProAlcohol) in 1975, Brazil has produced over 90 billion litres of ethanol from sugarcane. In 1989, 12 billion litres of ethanol replaced about 200 000 barrels of gasoline a day and almost five million automobiles run on pure bioethanol and a further 9 million cars run on a 20 to 22% blend of alcohol and gasoline. The ethanol industry is estimated to have created 700 000 jobs and many more indirect ones. Despite many studies which have been done on nearly all aspects of the programme, there is still considerable disagreement with regard to the economics of ethanol production in Brazil; this is because there are so many tangible and intangible factors to be taken into consideration.[50]

The average cost of ethanol produced in São Paulo State is currently (1990) about $0.185/litre. At this price, ethanol could compete successfully with imported oil if the international price of oil was $24/bbl.[51] Ethanol production costs have fallen 4%/year due to major efforts to improve the productivity and economics of sugarcane agricultural and ethanol production. Zabel[52] estimated that the cost of ethanol could be reduced by the year 2000 by 17% to $0.16/litre from the current estimated cost of $0.20/litre. This is equivalent to $32/bbl gasoline, in São Paulo. Others have concluded that ProAlcohol is economically feasible with both basic and high petroleum prices. However, in their low petroleum price scenario the analysis indicates that it would be more economical to use gasoline instead of ethanol.[53]

The costs of ethanol production could be further reduced if sugarcane residues, mainly bagasse were to be fully utilized. With sale credits from the residues, it would be possible to produce hydrous ethanol at a net cost of less than $0.15/litre, making it competitive with gasoline even at pre-August 1990 oil prices. With the BIG/ISTIG turbine systems for electricity generation, Ogden *et al* calculated that while producing cost-competitive ethanol the electricity cost would be less than $0.045/kWh. If the milling season is shortened to 133 days to possibly make greater use of the barbojo the economics become even more favourable.

USA: woody biomass

Research on short rotation woody crops (SRWC) in the USA was initiated in the mid-1960s, with major improvements in the technology largely secured over the past 10 years through numerous experimental trials. Most of this work has been funded by the USDOE and some by the US Department of Agriculture. Additional research is also being performed on herbaceous crops for biomass energy.[54]

In order to encourage the commercialization of SRWC, the economics of plantation systems are being evaluated over two general stages of research: first, feasibility studies of proposed commercial-sized systems; and, second, the scale-up analysis of actual commercial plantations. This latter effort includes economic and viability trials of 20 ha or larger of monoculture plantations established in several research institutions and private companies through cost-sharing programmes.

In the case of poplar hybrid plantations, the proposed design of the SRWC system centres on good agricultural sites at a density of 2 100 trees/ha, projected to yield an average of 16 tonnes (oven dry) ha/year. The estimated costs for individual operations and the delivered cost of wood chips have been calculated. The final budget reflects the establishment requirements of an agricultural site having good aspect and soil quality.[55] Strategies for disease and weed control have to be considered for long-term production.

Total delivered cost of wood chips from poplar plantations amounts to $56.36/tonne (1990$), equivalent to $2.9/GJ. Production costs account for $17.30; harvesting $8.45; transport $9.61; and storage and drying for $17.85. The single most important component is land price at $1 800/ha, which represents a typical value for a good maize production site.

Earlier estimates of the delivered cost for SRWC were in the range of $3 to $4.10 GJ (1985$) using then available technology. When possible technological advances in tree breeding and selection, cultural management, and harvesting are considered, the delivered cost could be reduced to $2/GJ for all regions of the USA. These estimates compare favourably with projected coal prices for the year 2000, which are forecast to range from $2.25 to $2.40/GJ for industrial and commercial users.

In the USA biomass generated electricity has become increasingly important over the last decade.[56] There are 9 GW of biomass electricity generating plants already in operation. Biomass energy of all types supplied nearly 4% of the total USA energy consumption equivalent to about 1.4 mboe/day, equal to hydroelectricity and almost as much as nuclear power, biomass could easily provide 2 mboe/day or more by the year 2005.

Sweden: woody biomass

In 1987 biomass energy-use in Sweden was equivalent to 65 TWh (234 PJ/year), representing about 14% of total primary energy consumption. There are plans which may increase the use of biomass up to 50% of total energy supply if there are politically directed changes concerning stopping the use of nuclear energy by 2010 and diversifying away from certain fossil fuels. National energy policy calls explicitly for greater use of indigenous and renewable sources of energy, particularly biomass energy. For example, in January 1991 the Swedish Government announced a five-year SEK3.8 billion (approximately $675 million) programme to develop alternative sources of energy, of which SEK1 billion (approximately $179 million) will be expended on energy from biomass.[57] The potential sustainable production of biomass energy is estimated to be some 730 PJ/year, about three times its current use. Details are available of current and estimated potential use of biomass energy and costs and also specific costs for willow plantations. The equivalent of about 360 PJ/year are generated today as forest residues or industrial byproducts, 60% of which are currently used for energy. Short-rotation energy plantations of willow and poplar trees, currently under development, could provide an additional 300 PJ/year.[58]

At the end of 1990 the total area of willow plantations on farmland was close to 2 000 ha and it is expected to reach 10 000 ha during 1993. In the next two decades as much as 300 000 ha may be planted with an energy potential of 15–20 TWh, an addition of about 3–4% to Sweden's energy needs. According to Ledin[59] the establishment of energy forests on farmland will receive a direct subsidy of SEK10 000/ha ($1 800). In addition there will be a subsidy during 1991 of SEK9 000/ha ($1 600) for conversion from cereals to alternative production, which will be lowered to SEK6 000/ha ($1 100) and SEK4 000/ha ($700) in 1992 and 1993, respectively.

The present market price of wood chips from forestry residues, about $3.4/GJ (1978$), reflects the current costs of recovering the residues separately from other forest-industry feedstocks (pulpwood and lumber). Integrating and recovery processes would lower the cost for such chips to $2.0–2.6/GJ. The cost of industrial byproducts (bark and sawdust) would be for handling and transport, implying essentially zero costs for on-site use. Wood chips from short-rotation energy plantation are estimated to cost $2.4 to 3.4/GJ.[60]

UK: straw

Biofuel production in the UK is small, approximately 1% of primary energy consumption, but could be significantly greater. The UK Department of Energy (UKDOE) considers five biomass technologies as being cost-effective in 1988: solid fuels from dry domestic, industrial and commercial wastes; solid fuels from straw; solid fuels from wood wastes and forest thinning; gaseous fuels from wet wastes; and gaseous fuels as landfill gas. These total a potential of about 8.8 mtoe of heat energy representing over 3% of current UK energy demand.

For example, the UKDOE has a programme to develop straw as a fuel – the country produces about 14 Mt of straw annually and half of this has usually been burnt in the field, a practice which will be banned from 1993. The aim is to use up to 1 Mt of straw by the year 2000 in partly modified boilers; at present only 166 000 tonnes of straw is used on farms as fuel.[61]

Straw is by no means a free source of fuel and the delivered costs can be relatively high. Generally straw in the field costs around £4 to £8/tonne (approximately (1990) $7.6 to $15.2) but by the time it is baled for on-farm use this has risen to £18 and £22–28 for industrial use ($2.5–3.1/GJ).[62]

The lower cost of straw compared to coal is counterbalanced by the relatively high cost of straw burning boilers which are generally more expensive than equivalent coal-fired equipment; this is because straw requires boilers with a high space volume and also the need to purchase bale conveyors and shredders. For farm-scale combustion systems (up to 300 kW), straw at on-farm prices can be competitive with coal at £70/tonne. Other sources indicate that straw can provide the lowest cost heating to the UK cereal growing farmer, about £0.85/kWh against £1.68 of natural gas and £1.67 for oil (1986 prices).

At Needham Chalks Co near Ipswich straw combustion has been shown to be economic in a rural industry given certain fuel oil prices. A 7 MW furnace using 2 000 tonnes of chopped straw per year is being used to dry 45 tonnes of chalk per hour.

At Woburn Abbey near London, a 0.8 MW boiler, using 400 tonnes chopped straw per year, heats all the central buildings cost-effectively and saves £20 000/year (about $38 000) compared to an oil-burning boiler.

ENVIRONMENTAL ISSUES

The world is facing serious environmental problems,[63] from erosion to pollution to climatic changes, which may have both known and unforeseen consequences. The developing world, for example, is losing an estimated 10–20 million ha of productive tropical land due to erosion, tree felling and uncontrolled clearing for agriculture; by the year 2000 some 275 million ha may have been destroyed since 1980. The sustainable production and conversion of plants and plant residues into fuels, offers a significant potential for alleviating the pressure for use of indigenous forests and woodlands as fuel. Along with the agricultural clearances these pressures have been the major threats to forest and tree resources, wetlands, watersheds and upland ecosystems.

Over the past 200 years, deforestation and now fossil fuel combustion have added CO_2 to the atmosphere resulting in an increased CO_2 concentration of 27% – half the increase has occurred over the past 30 years. The resulting greenhouse effect has been postulated to be already accompanied by an increase in the global average temperature of about 0.5°C and the global sea level has increased by 10–20 cm. If we do not change our lifestyles the global mean temperature may increase by 0.3°C/decade and the sea level by 6 cm/decade. Undoubtedly, the single most important factor in all these predictions is the rate of fossil fuel combustion. Biomass fuels make no net contribution to atmospheric CO_2 if used sustainably and can be regarded as a practical approach to environmental protection and longer term issues such as revegetation (including reforestation) and global warming.

Greenhouse warming and biomass sinks for CO_2

Reforestation and revegetation play important roles in reducing pollution. In 1980 the net release of carbon to the atmosphere from deforestation was probably in the range of 1 to 2 billion tonnes. In 1989 the net release was estimated to have been in the range of 1.5 to 3.0 billion tonnes.

There is ample evidence that the rate of deforestation has increased substantially since 1980 in several parts of the tropics, although there has been no comprehensive study of the tropics as a whole since then. In 1980 the rate of deforestation of tropical forests was 11.3 million ha and between 18 to 20 million ha in 1989. Over 150 million ha are expected to be deforested in the 1990s.

There are essentially three ways to decrease the use of fossil fuels: improving energy efficiency; developing renewable sources of energy; and expanding the use of nuclear power. Energy efficiency is an immediate need but must be accompanied by the deployment of renewable energies.

Renewable energies as a whole can play an important role in reducing pollution, particularly with the use of biomass for energy. A major global reforestation effort is a possible strategy to preserve and expand the world's forests, and to slow the pace of climatic change. As trees grow, they remove CO_2 from the atmosphere thereby slowing the CO_2 build up. Planting trees on a massive scale in the long term is one possible practical means of sequestering CO_2.

Collectively, a global strategy of halving tropical deforestation and planting the equivalent of a 130 million ha of trees in developing countries and 40 million ha in industrial nations could reduce worldwide carbon emissions from all human activities by about a quarter of current levels. It has been estimated that to remove and store two billion tonnes of carbon annually from the atmosphere using tropical forest trees (assuming a productivity of 15–25 tonnes of biomass/ha/year) would require the planting of 300 million ha. Sequestering the carbon for 20–60 years in the trees would stabilize CO_2 levels in the atmosphere and then using the biomass to replace fossil fuels would result in a decrease of CO_2. Possibly a better and economically feasible strategy recently suggested would be to substitute fossil fuel, especially coal with biomass fuels.[64] This study showed that while sequestering carbon in forests is a relatively low-cost strategy for offsetting CO_2 emissions from fossil fuel combustion, substantially greater benefits can be obtained by displacing fossil fuels with biomass grown sustainably and converted into useful energy using modern conversion technologies. This could be done using biomass gasification and turbines to generate electricity or by enzymatic hydrolysis of woody biomass to produce alcohol fuels. Biomass substituted for coal can be as effective as carbon sequestration, per tonne of biomass, in reducing CO_2 emissions; however, fuel substitution can be carried out indefinitely, while carbon sequestration can be effective only until the forest reaches maturity. Also, far greater biomass resources can be committed to fossil fuel substitution at any given time than to carbon sequestration

Table 7. Scenario for CO_2 emissions reduction via biomass energy-use[a] (Gt C/year).

2025	Electricity and alcohol from sugar cane[b]	0.7
	Electricity from kraft pulp industry residues[c]	0.2
	Energy from other residues[d]	0.8
	Total	1.7
2050	Electricity and alcohol from sugar cane	0.7
	Electricity from kraft pulp industry residues	0.2
	Energy from other residues	0.9
	Energy from biomass energy crops[e]	3.6
	Total	5.4

Notes: [a] A scenario for reducing global CO_2 emissions through bioenergy use only. This shows the potential but must be coupled with energy conservation and other measures.
[b] Assuming that sugar cane production grows at the historical rate of 3%/year, and that electricity is co-produced in excess of onsite needs with BIG/ISTIG technology of the equivalent.
[c] Assuming that chemical pulp production grows to 2025 at the rates projected to 2000 by the Food and Agricultural Organization (FAO), so that global production increases at an average rate of 3.1%/year.
[d] Since residues from other major forest product and agricultural industries are large compared to those from the sugar cane and kraft pulp industries, it is assumed that comparable emissions reductions could be achieved through use of some of these residues for energy.
[e] Assuming that biomass is produced on 600 million ha at an average productivity of 12 dry t/ha/year and that the produced biomass displaces coal and thus CO_2 emissions at an average rate of 3.6 Gt C/year.

because, first, producers will tend to seek biomass species with higher annual yields for energy applications; and, second, biomass for energy can be obtained from sources other than only new forests. Thus, biomass can play a larger role in reducing greenhouse warming by displacing fossil fuel than by sequestering carbon. Moreover, biomass energy is potentially less costly than the displaced fossil fuel energy in a wide range of circumstances, so that the net cost of displacing CO_2 emissions would often be negative. Thus bioenergy strategies have 'built-in' economic incentives that make them inherently easier to implement than many alternative strategies for coping with greenhouse warming. Table 7 summarizes a strategy for off-setting CO_2 emissions in 2050 by the use of biomass energy crops and residues.

These are possible long-term strategies but their implementation will prove extremely difficult unless there are substantial and long-term guaranteed incentives for tree growing which will provide impetus for local people, beside only short-term and artificially stimulated employment. These strategies must increase tree planting and revegetation generally in order to give optimal sequestering of CO_2.

Besides the removal of CO_2, forests provide many other ancillary benefits. Thus tree planting would improve the energy situation by providing fuelwood, may provide income generation, and would also have many important ecological effects associated with rehabilitating land such as soil erosion control, the maintenance of watersheds, improvement of local climates, the prevention of the destruction of wetland and upland areas, and so on. It has been estimated that 200 million ha needs to be reforested for reasons other than control of the greenhouse effect.

It is quite evident that more immediate benefits will be derived from increased energy efficiency and reduction in the rate of deforestation and devegetation. Even though halting deforestation will be very difficult, it appears to be a better option over the short term than attempts at very large-scale revegetation (afforestation). However, it is essential to understand the present use of biomass before planing revegetation and halting deforestation – otherwise well intentioned plans will come to nought. Table 8 shows a rough summary of CO_2 flows in sub-Saharan Africa to emphasize the role of biomass in comparison to fossil fuels and the uncertainties in calculating carbon fluxes which incorporate all forms of biomass vegetation.

The production of biomass whether it be in natural stands or with planted forests, woodlots or dispersed trees needs to be optimized in an environmentally sustainable manner. We discussed earlier, issues such as yield optimization with polycultures

Table 8. CO_2 flows in Africa: energy-use, forests and grasslands.

	$t\ ha^{-1}\ a^{-1}$	$Gt\ C\ a^{-1}$
Energy		
Emissions from fossil fuels (1988)[a]	–	0.18
Emissions from biomass fuels (1988)[b]	–	0.22
Forests		
Net emissions	–	0.23, 0.21[d],
from burning[c]		0.18
Net primary production[e]	16–22	2.1
Mean annual increment as wood[f]	–	1.4
Grasslands		
Gross emissions		
from burning[g]	–	1.09, 1.41
Net primary	7–9	1.86–2.39
production[h]	12	3.19
Net exchange of carbon	–	?

Notes: Areas of African forests = 267 million ha (Lanly (1982) (*Censu stricto*) = 137 M ha (ETC, 1990; Class 9) standing forest biomass = 12.2 Gt (equivalent to 88 t ha^{-1}) (ETC, 1990); areas of African grasslands = 591 M ha (Hao *et al*, 1989) = 667 M (ETC, 1990) (Classes 1 + 2 + 3 + 4); standing grasslands biomass = 4.5 Gt (600 M ha at 7.5 ha^{-1}) (average estimate based on Long *et al*, 1989; Hao *et al*, 1989).

Sources: [a] BP; [b] Scurlock and Hall; [c] Myers; Houghton; Hao *et al*; [d] closed forests only; [e] Lieth; Ajtay; [f] ETC; [g] Hao *et al*; Long *et al*; [h] Leith; Long *et al*, *op cit*, Ref 79.

instead of monocultures so ensuring some biodiversity, interplanting with N_2-fixing species so as to decrease fertilizer inputs and leaching, use of nutrient-optimized conditions to encourage the use of existing species and clones, and so on. We should also consider the desirability of achieving high levels of biological diversity which will require maintaining some of the land in biomass-producing regions in a 'natural' condition. For example, some bird species require dead wood and its associated insect populations for survival. Experience in Swedish forests suggests that maintaining a relatively modest fraction of forest area in such natural reserves is adequate to maintain a high level of species diversity. Studies of bird populations in short rotation forests in Ireland show that such plantations can have a favourable effect especially where different tree species are planted, coppicing is practiced, and there are numerous edges rather than large solid blocks of single clones or species. Research is needed to understand how best to achieve desirable levels of biological diversity under a wide range of conditions under which biomass might be grown for energy in the future.

While major expansions are needed for research efforts relating to large-scale sustainable biomass production, there is time for the needed research and extensive trials, because major bioenergy industries can be launched in the decades immediately ahead using as feedstocks primarily residues from the agricultural and forest products industries. Such use of residues can be done in an environmentally acceptable manner as long as monitoring, especially of soils, is performed and the mineral nutrients and intractable organic effluents are returned to the growing site. This is, for example, done in the sugarcane ethanol industry where stillage (fermentation effluents) is returned to the fields in diluted irrigation water. Similar practices should be normal management practice wherever large-scale removals of residues from agriculture and forestry are contemplated for energy production.[65]

The burning of biomass whether in the home or outside can have detrimental effects which need to be recognized and ameliorated. This is especially serious with open fires in closed domestic situations where eye, lung and other problems arise.[66]

Improved biomass stoves which reduce emissions and improve fuel efficiency are goals which must be pursued in parallel. Fortunately biomass is a low sulphur fuel and also produces less NOx than fossil fuels. These attributes, combined with its greater thermochemical reactivity, make biomass an attractive fuel especially compared to coal.

Burning of trees, shrubs and grasses results in the emission of a number of so-called greenhouse gases such as CO_2 (mainly), NOx, CO, CH_4 and other trace gases.[67] Large areas of forests and tropical grasslands are deliberately and accidentally burnt annually, besides the extensive use of biomass as a fuel. The influence of such biomass burning in the greenhouse-induced climatic changes has only been widely recognized over the last few years but is now being more thoroughly investigated. Such burning may not only pollute the atmosphere and result in increased CO_2 in the atmosphere (unless the biomass regrows in equilibrium), but may have serious long-term effects in soil carbon and erosion if the ecosystems are burnt too frequently and overused by man and animals so that soil erosion and other problems become endemic.

SOCIAL ISSUES

Most of the discussions of social issues around biomass production and use for energy have concentrated on the problems and opportunities in developing countries.[68] However, recently as a result of the increased use of biomass in developed countries and changing agriculture and forestry policies, serious thought is being given to the linkages between socioeconomic, environment, and land-use priorities. The issues in developed and developing countries are usually seen as being totally different but they now converge increasingly on the issues of land-use policies, subsidies and the environment. For example, North American, European and Japanese agricultural subsidies totalled over \$200 billion a year (or \$299 billion in 1990)[69] while energy subsidies in the USA have been estimated at \$44 billion a year or much more if all hidden externalities are accounted for.[70] These greatly distort energy and land-use patterns. Surplus agricultural land in the EEC is expected to reach 15 million ha in a few years while in the USA about 30 million ha are already under 'set-aside' or Conservation Reserve Programmes.

Biomass differs fundamentally from other forms of energy since it requires land to grow on and is therefore subject to the range of independent factors which govern how, and by whom, that land should be used. Thus, biomass energy is often considered problematic because of its varied facets, and because it interacts with so many different areas of interest, such as land-use rights, forestry, agriculture, societal factors, etc. For example, people differ in their attitude to land-use: at one extreme are those who put biomass exploitation above all, whereas others are primarily concerned with environmental matters.

There are basically two main approaches to deciding on land-use for biomass energy. The 'technocratic' approach tends to concentrate on the use of biomass for energy alone, ignoring other multiple uses of biomas. This approach starts from a need for energy, then identifies a biological source, the site to grow it, and then considers the possible environmental impacts. This generally ignores many of the local and more remote side-effects of biomass energy plantations and also ignores the expertise of the local farmers who know the local conditions. The technocratic approach has resulted in many biomass project failures in the past.[71]

The second approach may be termed the 'multi-uses' approach which asks how land can best be used for sustainable development, and considers what mixture of land-use and cropping patterns will make optimum use of a particular plot of land to meet multiple objectives, eg food, fuel, fodder, societal needs, etc. This requires a full understanding of the complexity of land use.

Since land for biomass energy production is so tied up with food production and environmental protection, these facets cannot be treated separately. The 'food *v* fuel' issue has been a heatedly debated land-use issue. To many people making fuel from crops has a strong moral connotation that serves to make the subject somewhat controversial. The subject is far more complex than has been presented in the past and one which needs careful examination, since agricultural and export policies and the politicization of food availability are greater determining factors.

Food *v* fuel should be analysed against the background of the world's real food situation (increasing food surpluses in most industrial and a number of developing countries) allied to the large production of animal feed, the increased potential for agricultural productivity, and the advantages and disadvantages of producing biofuels as part of the multiple benefits of land-use.

It is important to appreciate, however, that most developing countries are facing both food and fuel problems. What is needed is to actively encourage agricultural practices to take into account this reality and to evolve efficient methods of utilizing available land and other resources to meet food and fuel needs, besides the other products and benefits of biomass.

Brazil is an interesting case. The food shortages and price increases that this country suffered a few years ago were blamed on the ProAlcohol programme for alcohol fuel production. However, a closer examination does not support the view that bioethanol production has adversely affected food production. The root of the 'problem' lies deep in government economic policy in general, and agricultural policy in particular. Food shortages and price increases in Brazil have resulted from a combination of policies which were biased towards commodity export crops and large acreage increases of such crops, hyper inflation, currency devaluations, price control of domestic foodstuffs, etc. Within this reality any negative effects that bioethanol production might have had should be considered as part of the overall problem, not the problem. In fact, many national and local advantages have accrued from this programme, but it is undoubtedly not without its faults.[72]

Biomass plantations, especially eucalyptus plantations, have received adverse criticism in countries such as India and Thailand. However, most of these plantations are not grown for fuelwood but for other industrial uses such as pulp and for construction. There is a complex history behind the Indian and Thai experiences which should not condemn eucalypts as the villain of the piece, but should also look at the successes with eucalypts in Ethiopia, Brazil, Portugal, Hawaii, etc. Experience has shown that biomass energy plantations are unlikely to be established on a large scale in many developing countries, especially in poor rural areas, so long as biofuels (particularly wood) can be obtained at zero or near zero cost. Farmers in Malawi, for instance, are simply not interested in trees for fuel so long as they can get higher labour and monetary returns by planting other crops.[73]

Modernization of bioenergy production and use could bring very significant social and economic benefits to both rural and urban areas. Lack of access to a reasonable amount of energy, particularly modern energy carriers like electricity and liquid fuels, limits the quality of life of many hundreds of millions of people throughout the world. Since biomass is the single most important energy resource in rural areas of developing countries it should be used to provide for modern energy needs, eg agro-industry, irrigation pumps, refrigeration, lighting, etc.[74]

In addition, biomass energy systems should be perceived as providing substantial foreign exchange savings if they replace imported petroleum products, although the issue is not always clear cut since it depends on import substitution and export earnings. In countries like Brazil, with a long historical experience with technology for bioethanol production and use, there are substantial savings in oil imports and also foreign exchange earnings from alcohol-related technology exports. Zimbabwe similarly saves foreign exchange on petroleum imports while developing technical infrastructure which leads to import substitution. Thus we also need to consider the net benefit to a country if local resources used for domestic energy production could have earned more foreign exchange through exports.

Despite the fact that a large range of organizations have been created in developing countries to promote the development of small-scale production which is especially relevant to biomass energy, such institutions have generally not been very effective. Many governments and projects tend to be chiefly concerned with maximizing output rather than savings of capital and the generation of employment. High technology projects receive priority for political and prestige reasons. Any project that fails to reflect these key objectives is regarded as inferior to proven, capital-intensive methods. These factors inevitably result in most biomass energy related projects receiving low priority and/or ineffective implementation.

For example, in India, despite official interest in the development of small-scale industries, policy-making and investment has generally promoted large-scale and capital-intensive methods of production which is readily seen in the energy sector. Thus although energy efficiency and biomass-related energy generation appear much more cost-effective than centralized power generation, it is the latter which still receives priority in funding. Rhetoric and reality seem to be unbridgeable.[75]

Success and failure in biomass energy provision depends very much on the understanding of local incentives and barriers to change. Many innovations are pushed into the field because they interest the introducer rather than answering the basic needs of the people they try to help. Again, this is an especially detrimental attitude toward biomass projects which require very careful planning and long-term implementation, besides providing multiple benefits.

There are many other social issues which impinge on biomass energy. A number of these have been dealt with earlier: local employment, opportunities for entrepreneurs and development of skills, rural stability on an environmentally sound basis, local control of reserves, and promotion of appropriate political and economic infrastructures. At a more national scale the development of institutions capable of R&D and integrated land-use planning which encompasses the biomass dimensions seems essential if biomass is not to remain forever the poor, rural relation and not the environmentally-preferred modern fuel.

I have not dwelt on the other developing country biomass energy issues of urban fuelwood, fuel switching, poverty–population–environment–biomass interrelations, the 'fuelwood crisis', the 'fuelwood gap', forestry and agriculture and agroforestry, etc. All are relevant but have been well reviewed in a number of recent articles.[76] In developed countries concerns and issues in biomass energy evolve around risks and economics of land-use incentives, food surpluses, land surplus, pollution abatement strategies, environmental acceptability, alternative fossil, nuclear and renewable energy strategies, forestry policies, research policies, and so on. Extensive volumes and papers are published regularly which reflect on these issues.

CONCLUSIONS

Is biomass forever? Most certainly in the world as we know it, but whether it will forever be a source of fuel can be debated. With an increasing proportion of the world's population residing in developing countries, who usually lack fossil fuels and the easy means to import such fuels, it is essential that greater effort be put into producing and using biomass efficiently as a fuel since it is an available, indigenous energy resource which can be readily upgraded at all stages of production and conversion. One of the problems of wider acceptance of a modern role for biomass for liquid fuels, electricity and gases, in addition to its wide traditional use as a heat source, is that it involves land-use issues which make it very difficult to implement compared to other more centralized energy resources. There is an enormous untapped biomass potential, particularly in improved utilization of existing forest and other land resources (including residues), and in higher plant productivity. However, the enhancement of biomass availability (on a sustainable basis) will require considerable effort – there is no short cut to long-term planning and development in the biomass field.

It also needs to be recognized that biomass is used as an energy source for not only cooking in households, many institutions and service industries, but also for agricultural processing and in the manufacture of bricks, tiles, cement, fertilizers, etc. These non-cooking uses can often be substantial especially in and around towns and cities. Rural-based villages and small-sized industries are frequently biomass-energy driven and play a significant role in rural and national economies, eg in India these industries account for as much as half of the manufacturing sector.

Modern uses of biomass

The undeserved reputation of biomass energy as a poor quality fuel that has little place in a modern developed economy could not be further from the truth. Biomass should be considered as a renewable equivalent to fossil fuel; it can be converted to liquid fuel via ethanol, or electricity via gas turbines. It can also become the basis of a modern chemical industry via synthesis gas or ethanol as is occurring in Brazil. Biomass can serve as a feedstock for direct combustion in modern devices and is easier to upgrade than coal because of its low sulphur content and high thermochemical reactivity. Conversion devices for biomass range from very small, domestic boilers, stoves and ovens up to larger scale boilers and even multi-megawatt size power plants. Wider commercial exploitation on a sustainable basis awaits the development and application of modern technology to enable biomass to compete with conventional energy carriers.

There is a growing recognition that the use of biomass energy in larger commercial systems based on sustainable, already accumulated resources and residues can help improve natural resource management. If bioenergy were modernized (that is, the application of advanced technology to the process of converting raw biomass into modern, easy-to-use energy carriers such as electricity, liquid or gaseous fuels, or processed solid fuels), much more useful energy could be extracted from biomass than at present, even without increasing primary bioenergy supplies.

In favourable circumstances, biomass power generation could be significant given the vast quantities of existing forestry and agricultural residues – over two billion tonnes/year worldwide. For example, studies of the sugarcane industry[77] and the wood pulp industry indicate a combined power grid-export capability in excess of 500 TWh/year. Assuming that a third of the global residues resource could economically and sustainably be recovered by new energy technology, 10% current of the global electricity demand (10 000 TWh/year) could be generated. In addition, a programme of 100 million ha planting scenario, could also supply more than 30% of current global electricity demand. Efforts aimed at modernizing biomass energy should begin with applications for which economic analyses indicate there are favourable prospects for more rapid market development, eg the generation of electricity from sugarcane bagasse, alcohol fuels from sugarcane, and the production of electricity using advanced gas turbines fired by gasified biomass from various feedstocks.

If biomass energy systems are well managed, they can form part of a matrix of energy supply which is environmentally sound and therefore contributes to sustainable development. When compared, for example, to conventional fossil fuels, overall the impacts of bioenergy systems may be less damaging to the environment, since they produce local and relatively small impacts on the surrounding environment, compared with fewer, but larger and more distributed impacts of fossil fuels. It is these qualities which may make the environmental impacts of biomass energy systems more controllable, more reversible and, consequently, more benign.[78]

But biomass energy still faces many barriers – economic, social, institutional and technical. Biomass energy sources are very large and varied in nature, and the technologies for exploiting them span a very diverse range in terms of scale, stage of development, and development requirements to be able to provide a reasonably good understanding of the subject. While traditional biomass energy-use has long been with us, the future challenge is to focus on more economically justifiable, and environmentally sound, advanced biomass energy systems, while assuring at the same time that traditional production and use is as efficient as possible and also sustainable.

The author is most grateful for the inputs made over the years in our group by G. Barnard, J. Chadzingwa, P. de Groot, P. Moss, D. Newman, A. Rosenschein, F. Rosillo-Calle, J.M.O. Scurlock, K.A. Senelwa and J. Woods.

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Chapter 3

Solar Energy Systems

– assessment of present and future potential

H.-M. Kühne and H. Aulich

Average insolation levels are between two and four orders of magnitude higher than the specific demand for primary energy in both the industrialized and the developing world. This suggests that solar conversion technologies have a very considerable potential for application, provided that questions of storage and instantaneous release upon request can be adequately addressed. This paper discusses the present state and the future potential of solar thermal and photovoltaic (PV) technologies, and examines both the environmental implications of these technologies and the economics which determine their viability in the energy market. Although some significant cost reductions have been achieved, particularly in PV technology, solar conversion technologies are still not generally competitive against conventional fuels, and future cost reductions may be limited. It is argued that fiscal measures will be necessary if solar conversion technologies are to make a significant global impact.

Keywords: Solar energy; Photovoltaics; Solar thermal

The continuous supply of solar energy to the earth's surface is equivalent to a power of about 100 000 TW.[1] Approximately one-third of the radiation impinges on land area and should, accumulated over less than two hours, suffice to cover the whole primary energy demand by man for the period of one year.[2]

A share of 30% of the insolation is reflected back to space, 45% is converted to low temperature heat adding up to the heat balance of our planet, and 25% is converted in the earth's atmosphere for evaporation of water, for wind and wave energy, and marine currents.[3] These latter renewable energy sources are thus indirect forms of solar energy which may be tapped for the generation of mechanical power or electricity; an assessment of their respective potentials has been given in earlier editions of this journal.[4]

The only relevant chemical process harvesting solar energy is photosynthesis. The energy converted and stored this way accounts for less than a 0.1% of the original insolation, yet it is essential to all plant and animal life on earth. Solar radiation may be collected as visible light and also as heat. Technical systems described in the following try to mimic photosynthesis, both for electricity generation through direct conversion technologies, and fuel production in order to achieve energy storage.

A discussion of other technologies not directly converting visible light or solar heat is not within the scope of this article. For example, biomass has, in industrialized countries up to the past century, and in the developing world until today, been not only food and construction material but also the most important energy resource for man. Biomass may be converted to electricity through conventional combustion technologies, an essentially CO_2 neutral process contributing about 14% to the world energy consumption.[5] Other renewable energies such as wind or hydropower also have a long tradition; about 7% of the present world electricity production is based on the exploitation of these resources.[6]

Our energy-intensive industries are, to a large extent, ruled by energy economy rather than by issues of ecology. An extensive consumption of cheap fossil fuels has long been favoured, and questions of how to cope with the consequences have not been answered adequately. These days, as we start to worry about global warming, we have already achieved a 19% substitution of fossil fuels with renewable and nuclear power. However, with world energy consumption rising further at an increasing rate, a drastic increase in efforts to implement renewable technologies is considered indispensable.[7]

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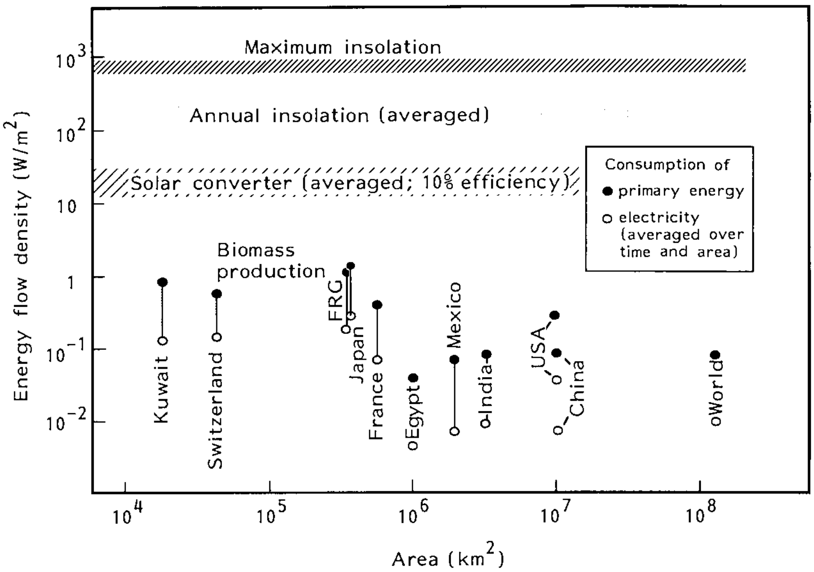

Figure 1. Comparison of energy consumption (1990, averaged) of selected countries with global insolation.

It will be shown that the economical potential of solar technologies is often not sufficient to compete with the prices of today's energy supply structures. Legislative measures and joint international collaboration seem necessary to an extent reaching far beyond established thinking.

THEORETICAL POTENTIAL OF SOLAR ENERGY SYSTEMS

In 1989 world consumption of commercial primary energy was equivalent to 10.2 billion tonnes of hard coal or 7 billion tonnes of oil.[8] In theory, solar energy could supply the total energy consumption by man, yet direct solar technologies are supplying less than 0.001% of present total energy consumption.

A typical value for the insolation on the earth's surface is, accumulated over the period of one year, about 1500 kWh/m^2. In the northern part of Europe or Canada some 1100 kWh/m^2 pa may be expected, and in large areas of the USA, Africa and Australia values exceeding an average of 2200 kWh/m^2 pa are not uncommon. Of course, the radiative power varies considerably during the course of the seasons, and as a consequence of the day/night cycle and local meteorologic conditions. If we think, nevertheless, of solar energy as being distributed evenly over the course of one year, the local insolation corresponds to an average intensity represented by a dotted bar in Figure 1, to which the energy consumption in a certain country of a given land area may be compared. In spite of the ratio between annual solar energy supply and total energy consumption being a function of both density of population and degree of industrialization, the average and peak insolation levels are by two to four orders of magnitude higher than the specific demand for primary energy and electricity in the industrialized and the developing world.[9] Only in urban areas or industrial agglomerates is more energy consumed than is supplied to the respective land area by the sun. Obviously, such areas will continue to depend on energy imports (to be supplied, preferably, by electricity).

Energy end-use: electricity, heating, transportation

Taking Germany as an example, it should theoretically be sufficient to equip just the unused outside surface of buildings pointing to the south with solar cells having a 10% conversion efficiency to cover more than the country's total electricity production.[10] Although some of the façades might not be suited for that purpose, the additional area required for solar collectors would be comparatively small. The potential for solar systems should be more favourable in developing countries with higher levels of insolation and lower specific consumption of electricity.

Heat generation currently accounts for about 45% of the commercial energy consumption (Table 1), yet it corresponds to only a small fraction of the theoretical potential for low temperature solar thermal systems.[11] Since it is relatively simple to construct solar heat collectors having a utilization of the solar radiation exceeding 10% (typical systems reach 30 to 70%), the theoretical potential for the imple-

Table 1. World consumption of commercial primary energy and emission of CO_2.

Energy end use		Total consumption of energy (TWh_{th})[a]	Energy from fossil resources (TWh_{th})[a]	CO_2 emission (million tonnes pa)[a]	Solar option
Electricity	World	28 538	20 145	6 300	Solar thermal plant
	EC	4 301	2 380	770	PV generator
Heat	World	37 435	36 377	10 000	Flat plate collector (low temperature)
	EC	4 136	4 136	1 160	Concentrating systems (mid–high temperature)
Traffic	World	15 820	15 820	4 400	PV + battery storage
	EC	3 371	3 371	940	Solar fuel (LH_2?)

Source: Vereinigung Industrielle Kraftwirtschaft, statistics, 1989–91.
Note: [a] Without non-commercial combustion of biomass and deforestation.

mentation of solar technologies should exceed heat demand by several orders of magnitude.

The situation in the traffic sector is somewhat more difficult: today's vehicles are equipped with internal combustion engines of a comparatively large mechanical power, a concept sustainable only if a liquid fuel such as gasoline, alcohols or liquid hydrogen is used. The electrical power produced if the cars were covered totally by solar cells would not be sufficient for cruising even at moderate speed.[12] Energy storage in high-performance rechargeable batteries might be one option. It is, however, a technological challenge still far from any satisfactory solution.[13] Given the present standard of vehicle technology, it seems more likely that eventually, at least in the long-distance traffic sector, a liquid fuel produced from biomass or solar electricity like liquefied hydrogen or methanol will have to drive solar vehicles.

As a formal result, the theoretical potential for the implementation of solar electricity and solar heat systems is far higher than the actual energy demand. However, the issue of energy storage and instantaneous release upon request becomes most important for all the three cases of solar energy end-use discussed so far.

CONCEPTS FOR SOLAR ENERGY CONVERSION

The solar radiation density on earth is rather low: the energy accumulated for one hour on a collector area of one square metre equals a maximum fossil equivalent of about 100 ml of gas oil. An efficient energy collection is thus extremely important for economic solar energy conversion. The quality of the solar irradiance is determined mainly by its intensity, spectral distribution, and by the diffusivity. These quantities determine the maximum energy conversion efficiency which is best for direct, high intensity insolation.[14]

Two fundamentally different concepts of solar energy conversion may be distinguished:

- solar thermal systems; and
- photovoltaic systems.

For solar thermal conversion, a heat carrying medium (usually a liquid or a gas) flows continuously through a heat receiver thus transporting the absorbed heat to the site of thermal energy use. The purpose may be space heating or the generation of electricity in a conventional bottoming steam cycle. Solar thermal systems may harvest the whole spectral range of the insolation (Figure 2). The maximum possible heat collection is limited by reflective, radiative, and convective losses in the receiving unit(s); in the case of electricity generation, the theoretical efficiency will be further limited by the Carnot factor which determines the maximum yield of all thermal processes. A certain system inertia is characteristic of all thermal systems; hence, the utilization of energy is delayed more or less with respect to the actual level of insolation. This may be advantageous since, to some degree, storage of solar energy or levelling of a discontinuous supply of the radiation becomes possible by just increasing the thermal mass of the system.

The principle of photovoltaic (PV) energy conversion is totally different. As with natural dyes in green plants, certain wavelengths in the solar spectrum are selectivly absorbed, generating an electrical current directly in the absorbing material. Technical systems all employ semiconducting compounds which have a so-called characteristics energy threshold: light quanta having an energy above this threshold are absorbed

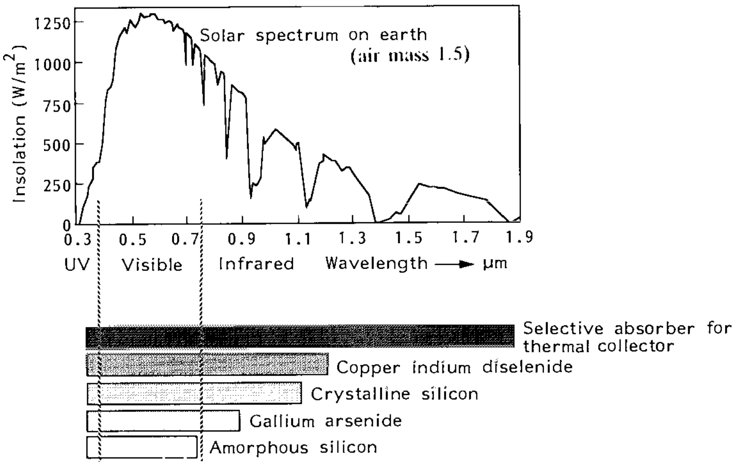

Figure 2. Portion of the solar spectrum absorbed in solar energy collecting materials.

and contribute directly to the electrical current; others of lower energy are lost as heat. The absorptivity of some selected solar cell materials is shown in Figure 2.[15] A significant advantage of photovoltaic systems is the fact that their conversion efficiency is virtually independent of both the system capacity (plant size) and incoming radiation intensity. As a consequence, a modular design from a few watts to the megawatt scale becomes possible without significant loss in performance even in the case of only moderate insolation.

Common technical concepts for PV and solar thermal systems are so-called flat plate collectors which are optimized for maximum absorption of the solar radiation. Flat plate collectors absorb both the direct and the diffuse part of the radiation. In the northern hemisphere, they are usually mounted at fixed tilt towards southerly direction.

By use of concentrating systems, higher energy flux densities may be achieved allowing for the use of more efficient converters for electricity generation. Concentrating systems have to track the course of the sun; one-axis tracking (trough concepts) and two-axis tracking (tower or single crystalline PV cell concepts respectively) are state of the art technologies.[16] Diffuse radiation is lost in concentrators which limits their use to southern areas with continental climate. Figure 3 presents, in a schematic way, different concepts and possible applications.

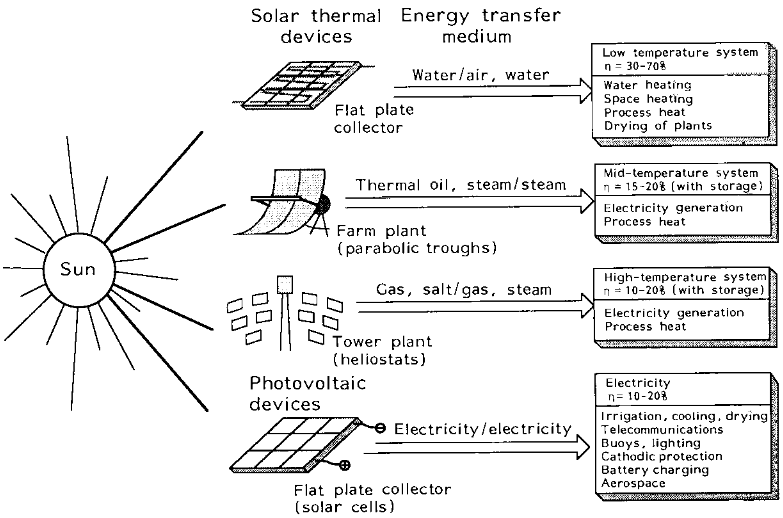

Figure 3. Systems for solar energy conversion (selection), efficiencies and application.

Table 2. Photovoltaic pilot plants (≥ 250 kW).

Project	Location	Peak power output (kW)	Commissioning
SOLARAS (Saudi and US governments)	Saudi Arabia	350	1981
Lugo Station/Hesperia (ARCO Solar/Southern California Edison)	California	1000	1982
Pellworm Island (EC) (AEG)	Germany	300	1983
Carrisa Plain (ARCO Solar/Pacific Gas and Electric)	California	6400	1983
Rancho Seco (Sacramento Municipal Utility District)	California	300	1984
Georgetown University Intercultural Center (Department of Energy)	Washington, DC	2000	1984
NEDO Utility System/Seijo (Japan MITI)	Japan	1000	1986
Austin	Texas	300	1986
Delphos (Italian government)	Italy	300	1987
RWE (RWE/Kobern – Gondorf)	Germany	340	1988
SOLAR-WASSERSTOFF-Bavaria (BMFT/Bayer,WiM/Bayernwerk/ BMW/Linde/MBB/Siemens)	Germany	280	1990
RWE (RWE/Lake of Neurath, Grevenbroich)	Germany	350	1990
PV USA (Davis)	California	750	1991

TECHNICAL POTENTIAL AND INSTALLED CAPACITY OF SOLAR SYSTEMS

In determining a realistic potential for solar energy converting systems, it must be borne in mind that the supply of solar energy is not continuous, by virtue of local weather conditions, the day/night cycle or seasonal variations in insolation level. In the power sector, the demand for electricity is usually met by a set of power plants and storage facilities which are sized to cover the expected maximum load level. As a consequence of the uneven consumer demand which is mitigated only if the electrical networks are largely interconnected, many power plants are kept for most of the time only at part load which makes their operation less economic.

If the peak demand for electricity coincides with the highest insolation level, as eg in countries with a high degree of climatization, solar energy systems might be a most interesting option to choose from. This way, otherwise necessary conventional power plant capacity may be saved. For other load curves, eg peak load in the evening hours, fossil back up systems could be employed for more or less solar assisted conventional power plants. The main target of such hybrid concepts is to save fossil fuels and potential emissions of noxious compounds whenever solar energy is available.

The presently installed power plant capacity (conventional thermal, renewable and nuclear) is worldwide about 2.7 TWe.[17] For the purposes of estimating a mid-term technical potential of solar systems, we may assume that 1% of power capacity to be replaced would be solar. Assuming further a relatively long useful life of some 50 years, market demand for solar power plants (including small solar generators) should already exceed a 500 MW production capacity pa. Since total power plant capacity is expected to rise beyond today's level by another 50–80% by the year 2020 with an increasing share of renewable technologies,[18] it seems quite realistic to assume a demand for an annual production capacity for solar systems of at least 5 GW (for comparison the present shipment of PV modules is about 50 MW pa). With a 100% utilization of a 5 GW pa production capacity, it would be possible to reach a solar share of just 2.8–3.5% of the total power plant capacity installed by the year 2020.

A selection of major photovoltaic power plants is shown in Table 2. Most major projects were either financed by national governments or local utilities. The main scope was to demonstrate the performance of different module technologies and other components such as tracking systems, power electronics (maximum power point tracking, dc–ac converter),

Table 3. Solar thermal power plants (selection).

Plant	Location	Electric power (MW)	Heat transfer medium	Commissioning
Farm plants				
SSPS-DRS	Almeria, Spain	0.5	Thermal oil, H_2O	1981
Aguas de Moura	Aguas de Moura, Portugal	0.56	H_2O	1985
NIO-PPS	Nio, Japan	1	H_2O	1981
SEGS I/II	Barstow, USA	2 × 13.8	Thermal oil, H_2O	1985–86
SEGS III/VII	Barstow, USA	5 × 30	Thermal oil, H_2O	1987–89
SEGS VIII	Barstow, USA	80	Thermal oil, H_2O	1990
Tower plants				
SSPS-CRS	Almeria, Spain	0.5	Na, H_2O	1981[a]
Eurclios	Adrano, India	1	H_2O	1981[a]
Sunshine I	Nio-Cho, Japan	1	H_2O	1982[a]
CESA 1	Almeria, Spain	1	H_2O	1983
Themis	Targassone, France	2	Molten salt, H_2O	1983[a]
STTF	Albuquerque, USA	5	H_2O	1977
CES 5	Krim, USSR	5	H_2O	1987
Solar One	Barstow, USA	10	H_2O	1982
Phoebus	Jordan	30	Air, H_2O	Project

Note: [a] Operation discontinued.

and battery storage options. The total capacity listed in Table 2 corresponds to a 14 MW peak power which is only a minute portion of the technical potential of the 5 GW capacity increase per year just estimated above.

The accumulated solar thermal power plant capacity is about one-third of a GW of peak power (see Table 3), the major share being due to the eight installed solar energy generating systems (SEGS) power plants in California. The apparent success of the SEGS farm concept arises from the fact that peak power electricity is produced for which Californian utilities pay an extra allowance over the usual refund for electricity fed into the public grid. The economics of this trough collector concept were founded, however, to a large extent on special tax credits which, in the meantime, have been withdrawn leaving further projects in the SEGS series abortive. The alternative solar tower concept is still in its demonstration phase and seems to be economically less promising than the farm principle.

In the private market sector for smaller photovoltaic and solar thermal collectors, economics rules over success and failure just as in the larger-scale power generation sector. Gaining a significant market share in private homes is regularly impeded for economic reasons whenever there is a connection to the utility grid or when conventional heating systems are already installed or have to be integrated in the buildings in any way to ensure comfort even in a harsh winter season. On the other hand, flat plate collectors with a solar energy utilization of better than 30% for low temperature space heating and production of warm water may be manufactured at relatively low cost and should be the first solar systems to prove economic also in moderate climate zones. They should also help to save fossil fuels and potential emissions.

An estimation of the technical potential for solar space heating should be possible by using the data for present fossil fuel consumption in this sector. At the end of the last decade, the West German primary energy consumption for space heating was some 500 TWh, about one third of the total consumption for heating purposes. A complete substitution with heat from solar collectors (sufficient thermal storage capacity assumed) would require a total collector area of about 1600 km^2, about two-thirds of the useful façade and roof area. Compared to this figure, the total European production capacity for solar thermal collectors is, again, at a rather low level: rising from 0.05 km^2 pa in 1976, it went up by a factor of six by the year 1980 to stay at about that value until 1989.[19] Assuming an average useful life of 20 years and a 100% utilization of the production capacity for another decade, about 0.4% of the German and only little more than 0.1% of the 1988 European primary energy consumption for space heating could be saved by use of solar thermal collectors. In view of the huge potential and the rather developed state of this technology, and in view of the social benefit in form of reduced CO_2 production, we may well ask whether the time is not ripe for some fiscal incentives to be offered to potential investors even though, in some countries, freezing winter temperatures require the use of a more sophisticated and costly technology ie with two hydraulic loops and integrated heat exchanging unit.

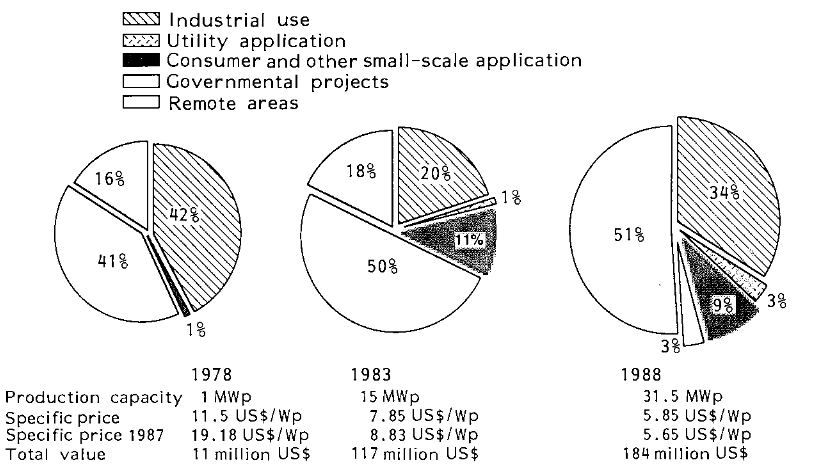

Figure 4. Evolution of PV application and costs (1978–88).

Source: Strategies Unlimited, *Five-Year Market Forecast 1989–94*, Report M32, Mountain View, CA, 1990 and *Overview of Photovoltaic Industry Status 1991*, Mountain View, CA, 1991.

PV sales in different market segments are subject to considerable fluctuation (Figure 4); apparently there has been little continuity in demand within potential application sectors. At the beginning of the 1980s a considerable portion of production was destined for publicly financed demonstration projects; demand has declined during the past decade but, in the meantime, has started again as a result of the US Department of Energy or the European Community attempting to deploy a total of more than 1 GWp of photovoltaic capacity by the year 2000. At present, the commercial market allows for only little more than 50 MW pa production of PV systems; the technical potential derived above for electricity generation from solar technologies was larger by two orders of magnitude (5 GW pa). Figure 5 shows that the actual production capacity for solar cells has been, for more than a decade now, utilized at only less than 50%, reflecting the relatively high price of PV systems.

ENVIRONMENTAL CONSIDERATIONS

Before the actual costs of solar energy systems and cost targets for the future are analysed, the question should be addressed as to what possible negative influence to the natural environment might be brought about by the large-scale fabrication and implementation of solar technologies.

First, there is the issue of the local albedo change. Solar collectors (PV or solar thermal) are optimized for maximum absorption of the solar spectrum ie they look more or less black. Visible light, otherwise directly reflected back to space, is now to some

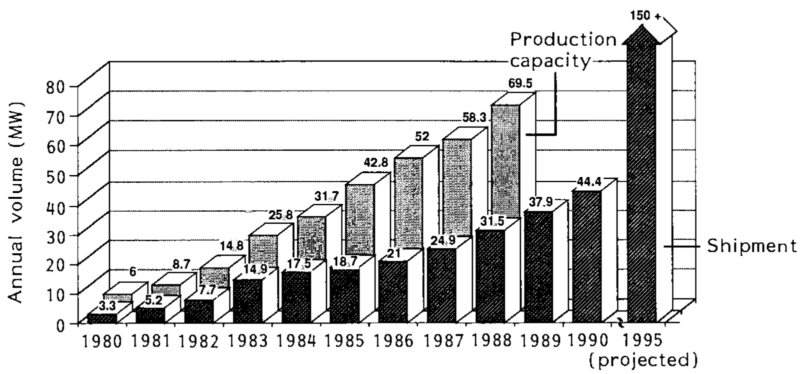

Figure 5. Photovoltaics: production capacity versus shipment.

Source: Strategies Unlimited, *Five-Year Market Forecast 1989–94*, Report M32, Mountain View, CA, 1990 and *Overview of Photovoltaic Industry Status 1991*, Mountain View, CA, 1991.

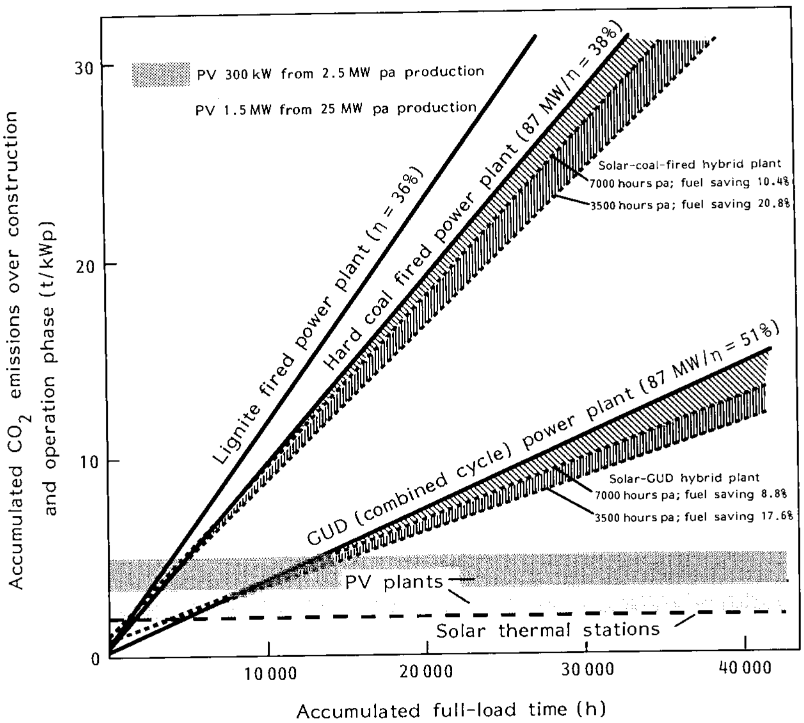

Figure 6. Specific emission of CO_2 for power plant construction phase and operation; comparison of PV and solar thermal plants with conventional combustion and solar assisted coal and *Gas und Dampf* (GUD) technologies. (GUD is a trademark for Siemens combined cycle power plants.)

degree lost to the atmosphere as low temperature heat. Distributed rather evenly over a large area, however, this additional heat should not be more serious a problem than the waste heat released by conventional central power stations, which seems quite commonly accepted by the public. In addition there is still the option of installing major solar power plants on otherwise unused arid areas in deserts.

Another question is that of the materials used. In solar thermal plants, concrete, metals and glass are the most important materials for which, as with components of conventional thermal power stations, no significant environmental problems are foreseen. In photovoltaic modules, however, semiconducting materials are employed which, either by themselves or by their production method, may be considered a potential hazard to the environment. In silicon modules only minute quantities of dopants are processed which, even if they were released from the modules to the environment, would be of little concern.[20] In the production process, however, these dopants have to be handled very carefully, and safety measures common to the chemical industry have to be employed.[21] Most of the advanced non-silicon technologies have to employ materials that require coordinated recycling after completion of service life; the question of environmental compatibility therefore has to be addressed carefully from case to case. With the tendency in all commercial sectors to legally bind the producer to take care responsibility for the eventual recycling of the product, this issue is given considerable attention when it comes to a decision about whether or not to initiate a new production process.

Finally, there is the question of the energy required for the manufacturing process of components for a solar power plant. This energy should be small compared with the energy produced during the useful life of the components. In Figure 6 we compare the specific CO_2 emission per kilowatt of installed power capacity accumulating during both the production process and the later operation period. The results may be summarized as follows. Compared to conventional power stations, considerably more specific (per kilowatt) energy is required for the production and assembling of a solar power plant.[22] If all components like absorbing units (PV or solar thermal), supporting structures, concrete foundation, electronics, wiring, etc are included, this energy consumption entails a relatively high specific emission of CO_2. For a single crystalline technology, up to 5000 kg CO_2/kW of installed PV peak capacity must be ascribed to the production process, and some 1900 kg CO_2/kW for a more favourable thin layer technology from a mass production line.[23] The latter value is also typical of the specific emissions associated with the erection of a solar thermal plant. The operation period of a purely solar technology (without fossil back-up systems) should, however, be essentially CO_2 neutral, provided the energy requirement for the service is ignored.

In contrast, the emissions of CO_2 from fossil power stations are accumulating over time; the specific release of CO_2 is dependent mainly on the efficiency of the fuel to electricity conversion process and the kind of fuel used. As a result, varying slopes are obtained in Figure 6 for the comparison of different conversion technologies. Compared to a conventional hard coal fired power plant, there is a net CO_2 saving for photovoltaics after some 1500–5000 hours of full load operation, depending on the kind of PV technology. In moderate climate areas, this should correspond to 16–54 months of service life, in more southern regions to about half that value. Compared to modern combined cycle plants using natural gas at efficiencies exceeding 52%, the specific CO_2 savings with solar systems are smaller: PV stations have lower accumulated specific emission only after 4500–12 500 hours in full load operation. This estimation should apply to comparable power plant size in the upper MW range. Obviously, smaller PV units could be compared only with smaller power sources like diesel generator sets which have a lower efficiency and thus higher specific emissions.

Several conclusions may be drawn from this discussion. Firstly, it is obvious that, as long as fossil combustion technologies are employed, energy saving is the most efficient way to reduce CO_2 emission. It is further obvious that, by replacing less efficient combustion technologies with eg modern combined cycle plants, a significant reduction of the specific CO_2 emission is achieved. Next, renewable energy conversion is not yet a CO_2 free process since, for the construction of the power plant, energy is required which may be fossil in origin. With increasing operation time of the renewable technology, however, the net CO_2 saving may assume considerable dimensions.

For the construction of a PV power plant based on the single crystalline silicon technology, a relatively large amount of CO_2 is released. For the, so far, relatively small PV market, there was no severe need for optimization of the energy balance of the production process. Large-scale manufacturing in future will increasingly have to account for the energy balance of the system and switch production processes and possibly materials; this has to be seen also within each entrepreneur's responsibility for most economic manufacturing facilities.

Finally, in order to reduce the relatively high energy requirement for supporting structures and foundations, PV modules should, as far as possible, be integrated in existing structures of buildings eg roofs, façades and possibly semitransparent windows in office buildings. Furthermore, increasing cell efficiencies in the future will yield a CO_2 balance of photovoltaic systems which is even more favourable.

SOLAR-ASSISTED OPERATION OF CONVENTIONAL POWER PLANTS

Except for special market segments (eg irrigation, ventilation), a purely solar power plant without storage facility of fossil back up system is not very attractive. One reason is the discontinuous supply of solar energy not adequately matching the load curve of a typical consumer population. A second reason, applying to solar thermal receivers, is the fact that, especially in the presence of single clouds, the output power may be subject to strong variations in time causing major problems with the regulation of the bottoming steam cycle. This is a strong argument for the concept of combined solar/fossil power plants.

If the peak load occurs during the evening hours, as is common in many industrialized and Third World countries, peak power can only be supplied by another, separately operated non-solar power station. Since both solar thermal and conventional power plants are based to a large extent on the same operation principles, numerous components identical to both systems may be integrated in one solar–fossil hybrid. In this way the total investment is significantly reduced over that required for two single plants. The hybrid system may be optimized for maximum saving of fossil fuel at constant load (fuel saving concept) or, alternatively, for maximum power increase by the solar part of the system (solar booster), if the peak load is expected in the afternoon hours.

In Figure 6 possible savings of CO_2 are shown for two selected solar–fossil hybrids: assuming a maximum 37% solar contribution to the output power of 87 MW (at 2200 kWh m^2 pa of insolation over 3500 hours pa), about 17.6% of CO_2 may be saved in a solar–natural gas fired combined cycle power plant with respect to a purely fossil operation. In a solar–

Table 4. Options for solar energy storage.

System	Operation temperature (°C)	Operational life Cycles	Years	Characteristic features[a]
Lead–acid	−10–50	150–1400	4	Developed, cost-effective system; medium energy density; not suitable for low temperatures; small cost reduction potential
Nickel–cadmium	−20–50	> 2000	5	Developed; high power density; robust; suitable for low temperatures; expensive system; problematic materials
Redox flow	0–50	> 1000	4/20	Demonstrated; low energy density; good lifetime for redox solution; no low temperatures; high cost reduction potential
Zinc–bromide	0–50	> 600	4	Demonstrated; good energy density; regular total discharge required; bromine problematic
Sodium–sulphur	280–350	3000	< 3	Demonstrated; high energy density; thermal self-discharge serious problems with lifetime; very expensive
Water electrolysis + fuel cell	80–120	1000	4	Demonstrated for solar application; poor energy yield (50%); expensive technology so far; CO_2 free fuel; essential technologies for solar hydrogen economy

Note: [a]Low temperatures are defined as below −10°C.

hard coal fired hybrid, the CO_2 saving may reach, under similar conditions, some 20.8% compared to the conventional case. As expected, under full load operation of the hybrid power plant (7000 hours pa), these specific CO_2 savings reduce to 8.8% (natural gas) or 10.4% for the coal fired plant. It is seen in Figure 6 that the specifically higher CO_2 release during the construction phase of the solar–fossil hybrid plant is compensated already after some 3500–7800 of solar full load hours which are reached in the sun belt after 1½ to 3½ years of service life.

The SEGS plants in California discussed above are based on the solar booster concept, for which a maximum 25% fossil contribution has been set by local legislation. With typically 1300 full load hours pa, these plants are able to supply peak load electricity in the afternoon hours only.

STORAGE OF SOLAR ENERGY

Strategies for a zero emission operation of a solar power plant must address the question of energy storage. Storage is most important in stand alone systems and in those cases where the interconnecting utility grid is too weak to allow for a significant energy transport over longer distances thus improving, at least to some extent, the local load factor.

In solar thermal concepts, heat buffering units may be integrated into the system; storage for more than a few hours, however, remains problematic. For photovoltaic generators, if major storage facilities such as pumped hydro power stations are not available, battery storage or the direct production of a solar fuel remain the only options.

In principle, several battery types should be suited to storing solar energy quite efficiently. The most common rechargeable battery system is the lead–acid accumulator, followed by the more expensive nickle–cadmium system. More interesting rechargeable batteries are in the development stage and not yet commercially available. The most important properties of selected storage concepts are summarized in Table 4.

The reason for the rather intensive development efforts for new batteries, both for load levelling purposes (eg the Moonlight Program in Japan) and for the storage of renewable energy, is the hope of significantly improving the economics of battery use.[24] The cost of electricity from a PV generator in southern countries has fallen already to a level (about 1 DM or US$0.6 per kWh) which is typical also of the cost of energy storage in lead–acid batteries. If PV systems are to gain a significant share in the power market, there will be no way round a parallel development of a reliable, long-lived storage system at costs significantly below present values.

One storage option is the production of hydrogen (H_2) through electrolysis of water. Something of a drawback of this concept is the rather poor efficiency of 50% or less for the production of hydrogen and its reconversion to electricity, even if advanced electrolysis and fuel cell technologies are employed. As a consequence, for short-time storage of up to a few days, batteries should retain their edge over hydrogen. However, since the raw material water is obtained at negligible cost compared with the energy content of hydrogen, H_2 has to be considered an interesting option whenever large quantities of cheap (or otherwise lost) energy have to be stored for a relatively long time. In concepts for the combined transport of electricity and hydrogen from eg Northern Africa to Central Europe, hydrogen is

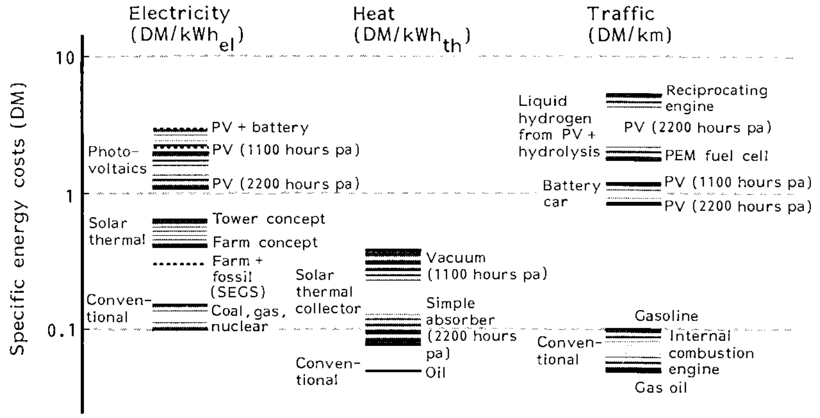

Figure 7. Solar energy end use: costs (as of 1992) for electricity, heat and road traffic, and comparison with conventional technology.[a]

Note: [a] For traffic no depreciation of vehicle is included. For reciprocating engine car 45 kWh/100 km assumed; for battery car 30 kWh/100 km; with PEM fuel cell 15 kWh/100 km.

assuming simultaneously the role of a transportable energy carrier and an energy buffer; for a detailed discussion we refer to the article by Winter.[25]

COSTS OF SOLAR ENERGY

As outlined above, the technical potential for the use of solar energy is exceeding the actual solar contribution to the total world energy consumption by several orders of magnitude. In other words, in spite of the option of tapping an energy source given to us at no cost (of supply), conventional combustion technologies are dominating the energy market by more than 80%. On the one hand this may be due to the enormous infrastructure built up for the exploitation and distribution of fossil energies to ensure a high degree of security of energy supply, especially in industrialized countries. On the other hand, the relatively high cost of investment in solar technologies has so far prevented its broader use. Figure 7 attempts roughly to compare the cost of solar energy with the competing energy prices that we are used to today. The costs were estimated on a 1992 basis (1 US$ = 1.65 DM) assuming a state of the art technology or cost targets for demonstrated technologies respectively.

It is seen that solar thermal collectors are close to being economic in countries with high solar irradiance if compared to the wholesale prices for fossil fuel; if retail prices for energy are taken for comparison, their operation is already quite economic.

Conventional central power stations are producing electricity at costs of about 0.1–0.15 DM/kWh not including transmission, distribution and storage of electricity, the latter being factors of considerable importance, especially in scarcely populated areas. Solar thermal and PV stations are more expensive by about a factor of 4–30, depending on the annual full load operation time and on whether battery storage is included or not. However, in many developing countries, electric grids are not very extensive or overloaded for most the time, and an adequate compensation of the reactive power is missing. Frequent power shortages are often the consequence. Decentralized solar power generation units close to load centres should significantly improve the security of power supply, especially if solar–fossil hybrid plants are installed. The costs for installation and operation of such hybrid plants should lie between purely solar and conventional stations.

The most expensive solar technology at present is photovoltaics with integrated battery storage. In highly insolated countries, about 2 DM/kWh must be projected, with half of the cost being due to battery storage. The high investment, however, may be compensated in the long run by virtually maintenance free operation. At present, small-scale PV power generation systems are most interesting for remote areas where an electricity grid does not exist.

The state of the art of battery technology for the propulsion of electric vehicles is barely satisfactory. Compared with liquid fuels and the use of internal combustion engines, the energy and power densities of all battery systems are small and the specific costs high. It seems that the use of electric vehicles will be limited, for some time to come, to densely populated areas.

With its high energy density (about half that of fossil fuels), liquefied hydrogen has the theoretical

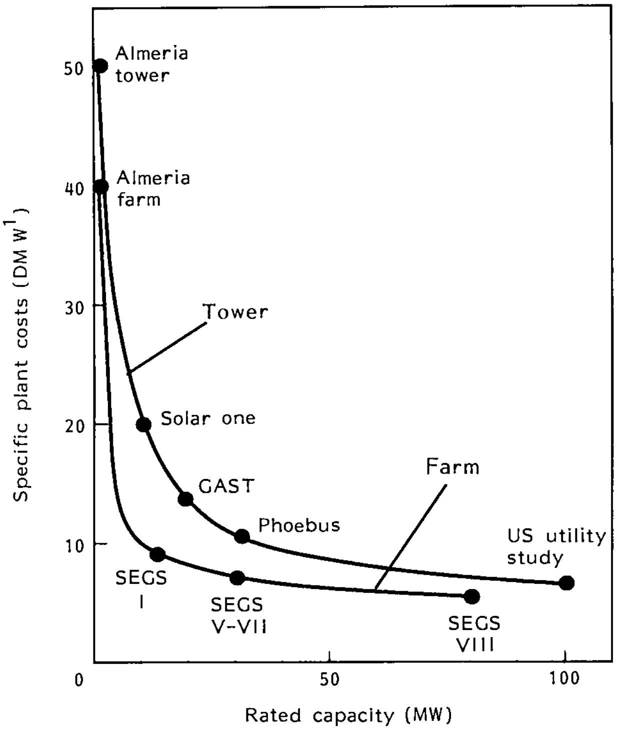

Figure 8. Specific costs of solar thermal power stations (farm and tower concept).

potential for widespread use, if problems with storage and handling (eg refuelling) can be solved. Produced from solar energy, the energy balance of the conversion chain through photovoltaics, electrolysis and liquefaction is rather poor, resulting in specific costs per kilometre that are higher by a factor of 20–50 compared to conventional vehicle technology (Figure 7).

So-called social costs accounting for the consequences of use of a given technology were not included in the estimation above (this concept would penalize conventional, non-renewable technologies.[26] It is our feeling that giving substantial figures on social costs is becoming increasingly difficult.

PERSPECTIVES FOR COST REDUCTION OF SOLAR POWER PLANTS

The cost reduction potential for solar components (eg collectors) is certainly higher than that of conventional components commonly used in established power plant technology. This tendency is reflected in Figure 8, showing the specific installation costs of the major solar thermal demonstration plants as a function of the power plant capacity. Apparently at some 5000 DM/kW, a limiting value is reached for the more favourable farm concept which is largely due to the trough collectors becoming a determining cost factor.

In photovoltaic power generation, a large number of standardized modules are switched together in order to get a sufficiently high dc voltage for the subsequent conversion to ac electricity. The costs for PV generators have long been determined mainly by the module component, the production costs of which have continuously decreased over the past years from values above US $40/Wp by the mid-

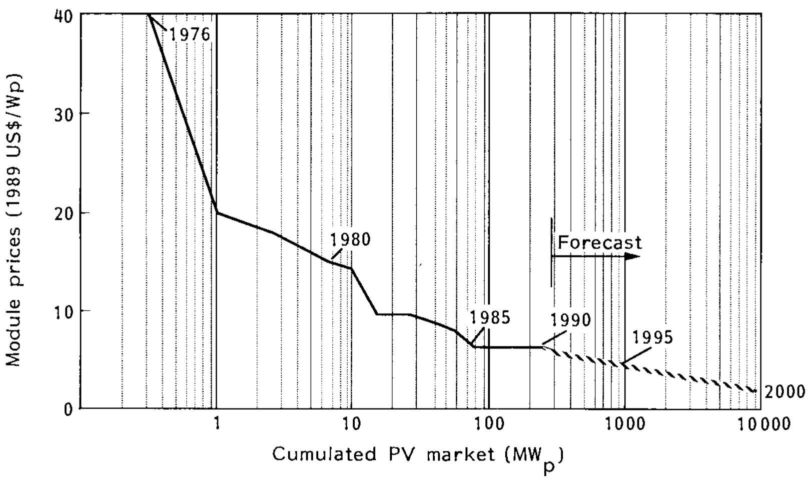

Figure 9. Evolution of prices with cumulated production of PV modules (1976–2000).

Source: Strategies Unlimited, *Five-Year Market Forecast 1989–94*, Report M32, Mountain View, CA, 1990 and *Overview of Photovoltaic Industry Status 1991*, Mountain View, CA, 1991.

1970s to now less than an average of US$6/Wp. For a mid-size plant (eg 100 kW) these costs have to be doubled in order to account for the mechanical and electronic components of a complete PV generator. Extrapolation indicates that upon further increase in production capacity module prices stabilizing below US$4/Wp can be expected. Part of this further cost decrease should be achievable by a better utilization of the production capacity, and part by new technological approaches. There is the prospect of a significant cost reduction, especially for thin layer PV technology, since in laboratory-scale experiments sizeable improvements in the understanding of several materials' properties and cell design features have been achieved during the past years. At the same time, though, efficiency improvements of industrial modules have been slow. To reduce the production cost of PV modules significantly, both increases in cell efficiency and production on an industrial scale are necessary. With increasing worldwide shipments of PV modules, large-scale factories should become a reality. However, not only the production costs of modules, but also those of electronic components such as charge regulators, inverters etc have to be reduced as well.

Larger utility-scale demonstration programmes in the megawatt range, as initiated by the US DOE, US, German, and other countries' governments and utilities, seem quite appropriate to test and further improve PV modules from different pilot production lines. Decentralized PV electricity generation programmes in countries with highly developed electricity grids like the 1000 roofs initiative by the German government are helpful ways of gaining experience and achieving a reduction in fossil fuel consumption. Such programmes should thus be pursued further. On a global scale, however, if we want to boost the use of renewable (including solar) technologies considerably beyond its present level, there seems to be, in a free market economy, no way around raising the prices of fossil fuels.

CONCLUSION

Compared to the enormous theoretical and technical potential of solar energy conversion, little use is being made so far of already developed and demonstrated solar technologies. Solar thermal and photovoltaic generators are reliable and safe, and they offer the prospect of significant fuel savings in combined solar–conventional heat hybrid power plants as well as in stand alone systems. Solar thermal power plants (with an integrated fossil back up system) are close to being economic in areas with high solar irradiance. The use of PV generators is, so far, limited to small-scale remote applications.

For strategies of a massive CO_2 reduction, energy conservation together with the broad-scale implementation of renewable technologies, including the combined use of solar–thermal and PV systems, become indispensable. But the question of energy storage has to be addressed again. Present battery concepts are based mostly on the lead–acid accumulator, a mass product for which a further significant cost reduction is required but seems unlikely. The development of alternative storage systems should thus be supported further.

A significant reduction in the cost of PV systems has already been achieved, but further reductions are still necessary. For a large-scale use in the power sector, production processes must be developed for efficient thin layer modules requiring less energy than the presently prevailing crystalline silicon technology. PV components should preferably be integrated into existing structures of buildings, thus reducing or avoiding the need for investment in components such as supporting structures or foundations. In addition, feeding power into the electricity grid would reduce emissions and limit the need for expensive batteries.

Subsidies for the build up of large-scale production lines for PV components may be one option to enhance the dissemination of solar energy systems. On a shorter timescale, however, major worldwide demonstration programmes for remote applications, and for feeding solar electricity into the public grid by means of decentralized and large-scale central systems, seem more appropriate to improve our understanding of PV systems thus stimulating, at the same time, the demand for building large-scale PV factories.

What we need further are concepts that encourage technical innovation by putting inefficient, obsolete combustion technologies at a disadvantage. Penalizing pollution and emissions seems the most effective approach, and it should be pursued in a determined but careful way. The problem has long become a global one and, given the variety of technological systems that engineers have invented, politicians have now to become more involved in the decision making process on what energy options should be chosen for the future.

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[11]*Op cit*, Ref 2.
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[13]Several battery systems are being developed and demonstrated; so far, typical lifetimes are two to four years; a typical battery set for a range beyond 100 km (moderate cruising power) costs $5000–20 000.
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Chapter 4

Wind Energy

– experience from California and Denmark

Paul Gipe

Man has long sought to harness the wind, but not since the wind was used to sail the world's seas and pump water from the low-lands of northern Europe has wind energy been used on such a grand scale as now found in California. Wind energy has once again come of age. The wind industry's tremendous growth during the 1980s has pushed the technology beyond that of merely another 'alternative'. Wind's success in California and Denmark demonstrates that the technology works, that it can produce sizable amounts of electricity, and that it is economically competitive. Though it suffered severe growing pains, and struggled through a stormy adolescence, wind energy is now ready to take its place among conventional resources. This paper examines how wind energy has come of age in California.

Keywords: Wind energy; Solar energy; Electricity generation

Not only do wind turbines today provide commercial bulk power in California, Hawaii, Denmark, Germany, Spain, the Netherlands, and India, but they also serve thousands of rural residences and remote villages around the world. Yet unquestionably wind energy has made its greatest mark in California where the state has become a powerhouse of wind, geothermal, biomass, and solar-electric technologies. With a population of 30 million sprawled over a land area twice that of the UK, and the world's sixth largest economy, California has become an international model for developing energy diversity.[1]

California wind power plants currently account for 80% of world wind generation[2] (Denmark produces much of the remainder) (Figure 1). After only one decade of development, wind turbines provide about 1% of the electrical generation in the State.[3]

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The 15 000 wind turbines in California generate about 2.5 TWh/year, more than enough electricity to meet the residential needs of a city the size of San Francisco or Washington, DC. California's wind industry now produces the primary energy equivalent of more than 4 million barrels of oil per year – 16 times the oil spilled by the Exxon Valdez in Prince William Sound. California wind power plants alone generate as much electricity as that produced by a medium-size nuclear reactor, or a compatible coal-fired power plant (Figure 2).

While not without problems, wind energy represents a remarkable success story of the scramble to develop alternative energy after the oil embargoes of the 1970s.[4]

THE CALIFORNIA EXPERIENCE

Wind development concentrated in California during the 1980s for several reasons, effectively launching the commercial wind industry out of the doldrums of government-sponsored research. In 1978 Congress passed the National Energy Act to encourage conservation and the development of the nation's indigenous energy resources. The act included provisions that both opened the utility market to non-utility generators (dependent power producers) as well as offered tax incentives to stimulate development.

The Public Utilities Regulatory Policies Act (PURPA), one of the Energy Act's many parts, guaranteed a market for the electricity generated by independent producers. It required utilities to buy electricity at a fair price and to sell back-up power to independent producers at non-discriminatory rates. Implementation, however, was delayed until the early 1980s as each State sought to interpret Federal regulations.

Federal tax credits (15%) created by the Energy Act took effect almost immediately. But they were

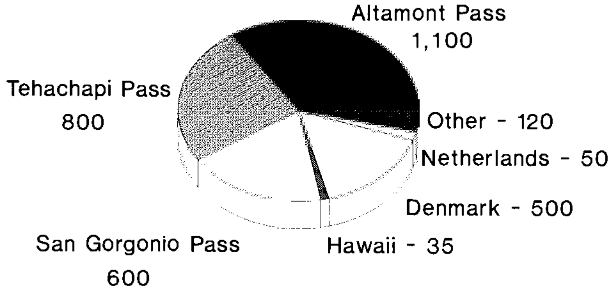

Figure 1. World wind generation 1990 (kWh).
Source: Paul Gipe & Associates, 1991.

of little immediate help in spurring the industry's growth because PURPA's implementation, and the market it opened, lagged behind. Even with PURPA, utilities were reluctant to negotiate power sales contracts or interconnection agreements with either homeowners who wished to use a wind turbine for supplemental power, or third parties, such as entrepreneurs, who wished to develop wind power plants and generate electricity commercially.

The situation changed in California just before year-end 1979. The State's Public Utility Commission (PUC), which regulates electric utilities, fined PG&E (one of the USA's largest investor-owned utility) $15 million for not considering conservation and alternative energy in their mix of future generating plants. Attitudes among the State's utilities towards non-utility generators suddenly softened.[6]

The following year California's ambitious governor organized a conference to attract financial interest in commercial wind development. The governor sought development in areas of California where State-funded studies had found developable wind resources. In late–1981 private firms installed the first wind turbines in two of the State's three windiest passes.

Despite this progress, development proceeded slowly. So slowly that in 1983 the PUC fined Southern California Edison Co $8 million for failing to follow orders to accelerate development of cogeneration and other alternatives. Widescale development of these 'alternative sources' became possible only after the PUC established standard contract terms, including one (Standard Offer No 4) which fixed prices over 10 years based on forecasts by each utility of increasing fuel costs.

California eventually grew to dominate not only US but also worldwide wind development because of its

- *Resources:* the State has some of the most energetic winds in the USA.
- *Regulatory climate:* the State, until the mid-1980s, has the most favourable purchase power rates and the most cooperative utilities in the nation.
- *Available land:* low-cost land was in abundance with few land-use conflicts.
- *State tax credits:* 25% State tax credit in addition to the 15% Federal tax credit. (The credits, though, were not simply additive.)
- *Investment climate.* New ideas, such as wind plants, are more readily accepted in California than anywhere else in the USA.

Even in such a large State as California, land is an important commodity. The availability of land and its low cost enabled the industry to gain a foothold with what was, at that time, a marginal technology. Subsequent development has concentrated in three mountain passes: the Altamont Pass, east of San Francisco; the Tehachapi Pass, north of Los Angeles; and the San Gorgonio Pass, east of Los Angeles. All three areas are sparsely populated where cattle grazing was the dominant land-use before development began (Figure 3).

By the late-1980s a dozen firms were actively developing wind plants in California. By 1991 these privately-held, non-utility producers were operating 1 5000 MW of wind-generating capacity (Figure 4). Three firms account for about one-half of California's wind generation: US Windpower, SeaWest Energy Group, and Zond Systems.[7]

The industry grew steadily until 1988 when the total number of turbines installed and the capacity they represented suddenly declined. The dip in cumulative capacity reflects the removal of inoperative turbines, many of which were hastily installed during the industry's rapid growth in the early 1980s. These turbines performed poorly, if at all and contri-

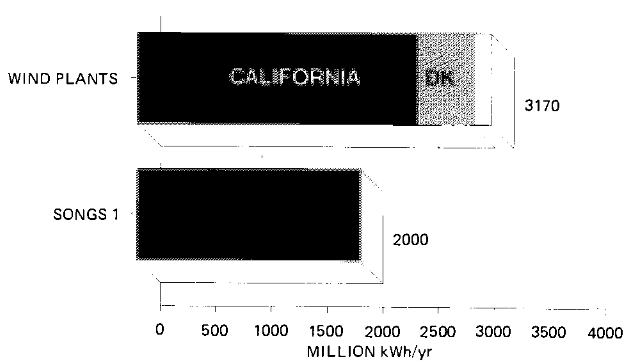

Figure 2. Comparison of wind generation with output from Southern California Edison Co's San Onofre nuclear generation station No 1 (a 424 MW reactor with an historical capacity factor of 60%).
Source: Paul Gipe & Associates, 1990.

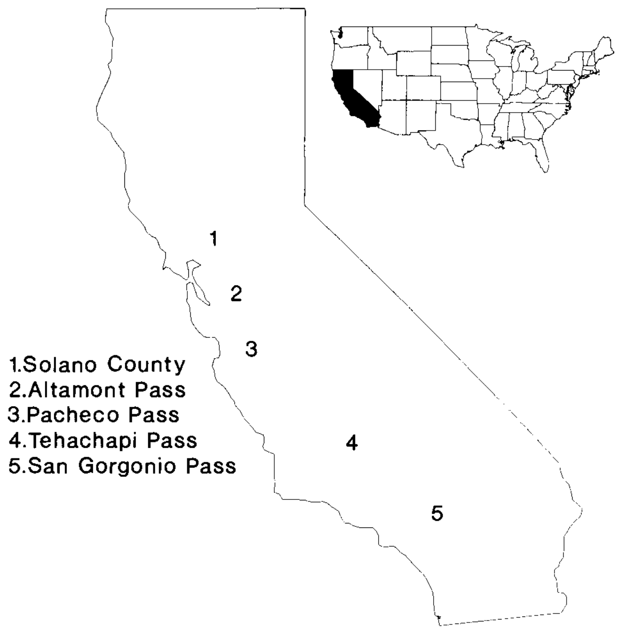

Figure 3. Location of California wind power plants.

buted little to total generation. They also severely detracted from the overall performance of the industry.

Generation has grown rapidly since the first turbines were installed in 1981; quadrupling from 1983 to 1984, tripling from 1984 to 1985, and nearly doubling from 1985 to 1986. Increases in generation have moderated somewhat since 1987 because new turbines represent an increasingly smaller proportion of the total installed, and because the major gains in productivity – by improved reliability – have already been achieved (Figure 5).

By 1991 wind generation had become one of the largest producers of solar-generated electricity in California. Wind plants generated 10 times more than photovoltaics, four times that of solar-thermal

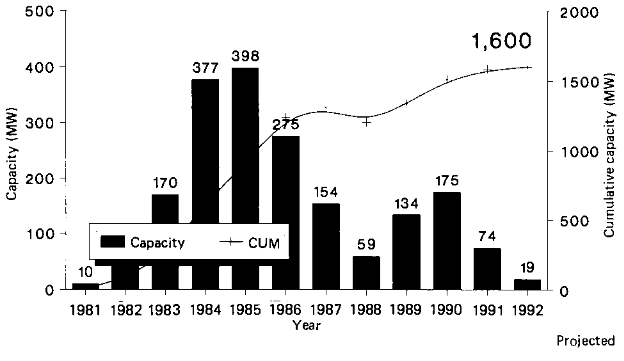

Figure 4. Annual installation of wind generating capcity in California, and estimate of cumulative total by the end of 1992.

Source: CEC; CEC PRS; and others.

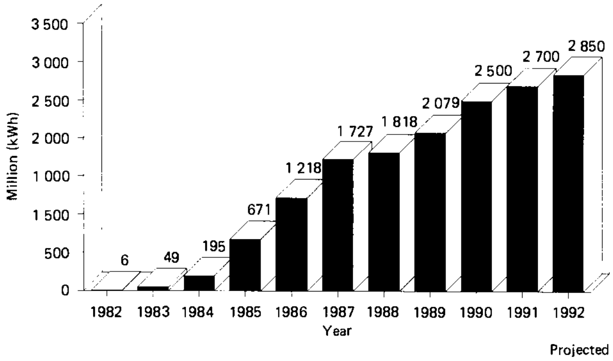

Figure 5. Statewide wind generation in California.

Source: CEC; CEC PRS; and others.

(parabolic trough) technology, and more than two-thirds as much as biomass plants burning wood and agricultural wastes (Figure 6).

The changing California market

Since the mid-1980s the California market for wind energy has changed dramatically. The Federal tax energy credits that fueled California's growth expired at the end of 1985 and were not renewed. The 10% Federal investment tax credit, which could be applied to most investments in equipment whether wind turbines or industrial machinery, was also allowed to expire at the end of 1985. California's State tax credit was reduced to 15% in 1986, and expired the following year.

As a result of the changes in the tax code, investments in wind energy became less attractive than they once were. Though wind is still an economic investment under California conditions, the loss of tax credits reduced the amount of capital flowing to the industry. Financiers now raise capital from conventional sources, such as banks and leasing

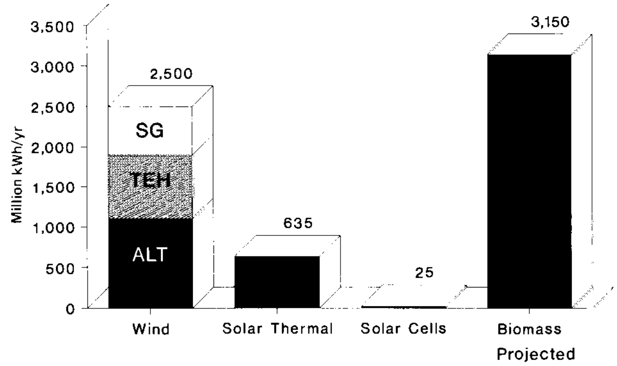

Figure 6. Comparison of wind generation in California with generation by other forms of solar electricity.

Source: Paul Gipe & Associates, 1991.

companies, in the international market. However, despite the loss of tax subsidies, 53% of California's wind capacity has been installed since the Federal tax credits expired.

Equally as damaging to the industry's growth as loss of the tax credits was a dramatic change in the State's political climate, from public encouragement to open hostility. By the mid-1980s both the State and the two major electric utilities were publicly warning about an 'oversupply' of alternative energy. The ensuing battle between independent producers, regulators, and the utilities retarded growth by shaking investor confidence in the long-term contracts that became the backbone of the industry. The change in attitude also limited the availability of new contracts between wind companies and the utilities.

Current development uses fixed-price contracts negotiated in 1984. By the end of 1992 the existing inventory of undeveloped, fixed-price contracts will be exhausted. Unless new contracts are issued in the interim, expansion of wind energy in California will come to a halt.

Recently, however, the trend towards discouraging further wind development appears to have reversed directions. In late-1990 the California Energy Commission (CEC) issued a widely publicized report concluding that new generating capacity will be needed during the 1990s and recommended that 50% of this new capacity should come from renewables. The PUC, which has jurisdiction over contracts between utilities and non-utility generators, has yet to act.[8]

THE DANISH EXPERIENCE

Though California leads the world in wind generation, it has done so in part with Danish technology. About one-half of the California's wind capacity was built in Denmark and imported to the USA by Californian companies.

The development of wind energy in Denmark followed a far different path than that in California. Unlike the USA where early wind turbine development was concentrated in the hands of the aerospace industry, Danish wind technology grew out of the agricultural sector as a natural byproduct of the Danish economy.

Denmark is a nation of farmers, light industry, and small landholders with a population of five million distributed uniformly throughout the flat countryside, and exports mainly food and agricultural implements. Denmark's position jutting into the stormy North Sea, with its 5 000 miles of indented coastline and open agricultural land, also endows it with a significant wind resource not unlike that of the American Great Plains. This is fortuitous, for Denmark is a net importer of energy.

Danes have a cultural predisposition towards using wind energy. Not only are windmills still a common sight on the landscape, but wind turbines were used successfully during both world wars to meet domestic demands. The government, as an outgrowth of this experience, chose wind energy as one means to wean the country from imported oil. With ample wind and government encouragement, independent-minded Danish farmers soon created a demand for a new generation of wind turbines. Danish farm equipment manufacturers quickly turned their attention towards this emerging market.

The broad distribution of people across the landscape, a good wind resource, and a manufacturing sector accustomed to building heavy, reliable machinery for a rural market were the key ingredients to launching a successful wind industry. Because of the country's size, manufacturers could also service their own turbines often directly from the factory. This enabled them to learn quickly from their mistakes and to keep their turbines in operation as physical proof to potential buyers that their machines were a good investment.

These conditions contrast markedly with those in the USA. Early US programmes poured research money into the aerospace industry in an erroneous belief that they, and only they, were capable of building successful wind turbines. However, US policy failed to realize that wind turbines, though in some superficial ways resembling aerospace technology, are not aircraft. Wind turbines must produce cost-effective electricity. To do so they must perform like other power plant machinery: reliably over long periods of time with as little maintenance as possible. As a consequence, early US designs resulting from government research programmes were marvels of the aerospace arts, highly-efficient turbines operating at high speeds. Unfortunately, these designs proved both noisy and unreliable. Today no US company builds wind turbines and no designs from that period remain on the market.

The one successful US manufacturer of machines for utility-scale applications, US Windpower, designed and built its turbine without US government assistance. And – after several refinements of the basic design – US Windpower has become the world's largest wind turbine manufacturer, as well as the world's largest producer of wind-generated electricity.[9] Unlike US Windpower, which was well-financed (and has remained so), all other US manu-

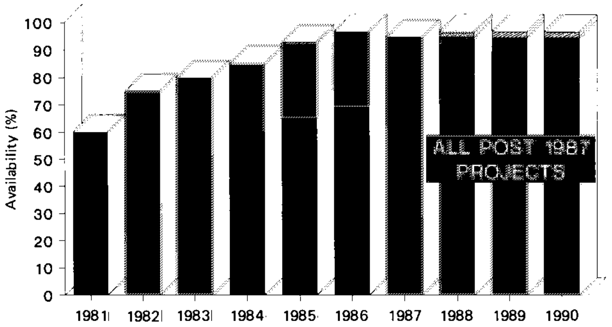

Figure 7. The availability for operation of selected California wind power plants. All projects installed since 1987 have been available for operation 95–97% of the time.
Source: R. Lynette

facturers were small, undercapitalized firms with little staying power.

The Danish firms that entered the market were medium-sized manufacturers, experienced in marketing to a rural clientele, and were moderately financed. This has not prevented several noteworthy failures of Danish manufacturers and the restructuring of the Danish industry, but it has permitted them to establish a manufacturing base that remains a major force on the world stage.

The huge geographic size of the US market, the vast difference in terrain and wind speeds also hindered the development of a successful domestic indsutry. As in Denmark, nearly all early marketing efforts focused on rural applications for homes and farms. This resulted in the distribution of machines across the expanse of the continent, many of which were installed in areas of low winds. The small US firms, and their distributors, could not adequately service such widely scattered turbines. The turbines that failed often remained inoperative and discouraged potential buyers from following suit. When these small firms encountered technical problems they were often unable to correct them, and they quickly failed.

Denmark has consistently followed a national policy of promoting a strong domestic market for wind energy. To launch a domestic industry and encourage the use of alternative energy the Danish parliament provided tax benefits worth 30% of the initial cost. Gradually, as the industry proved its success on the home and international markets, these subsidies were reduced. By the late-1980s the tax benefits no longer applied to turbines in commercial wind plants. By 1989 these subsidies had been reduced to only 10% of the turbine's initial cost, and in 1990 they were eliminated entirely.

Even with reduced subsidies, Denmark's home market still accounts for about 300 turbines/year. Some 50 000 Danes – 10% of the population – have invested in Danish wind energy; one-fifth in Danish wind plants built in California.

In contrast to California, most turbines in Denmark serve homes, farms, or small businesses, and most installations comprise only one turbine. There are few wind plants, and these are small by US standards. Wind plants account for only one-fifth of the turbines erected in Denmark. Most Danish wind power plants are small enough that they themselves could be viewed as clusters of distributed, or individual, turbines. Both the number and size of Danish wind plants are a fraction of those in California. The average size of Danish wind plants varies from 10 to 50 turbines each – the single, largest project using 100 turbines. By the late-1980s projects in California had reached 300–600 turbines.

Despite the differences between California and Denmark, development of the technology has progressed similarly on both sides of the Atlantic.

PRODUCTIVITY

Wind turbine productivity has improved dramatically during the past decade in both California and Denmark. Wind plants in the Altamont Pass, according to PG&E, are meeting about 70% of their energy goals.[10] By the late-1980s new California projects were consistently meeting their projections. US Windpower, which generates nearly 25% of the State's wind energy, produced 90% of their estimated output in 1988 and 83% in 1989 (Figure 7).

The productivity of California wind plants has increased by more than 40% since 1986 when the State of California began tracking production (Figure 8). The specific yield has increased from 475 kWh/m^2 in 1986 to 685 kWh/m^2 of rotor swept area in 1989 at an average capacity factor of 18%. Better performing projects deliver from 800 kWh/m^2 to 1 200 kWh/m^2 and capacity factors of 20–30%. California's most productive turbines stand atop Whitewater Hill in the San Gorgonio Pass where San Gorgonio's Farm's 200 turbines produced 1 200 kWh/m^2 in 1989 at a capacity factor of 39%.[11] Currently, performance projections – tempered by experience – for good sites in California average about 1 000 kWh/m^2.

Improvements in Denmark resemble those in California. By 1989 more than two-thirds of the privately owned wind turbines in Denmark, nearly 2 000 units, were regularly reporting production and availability data to the Danish Association of Wind-

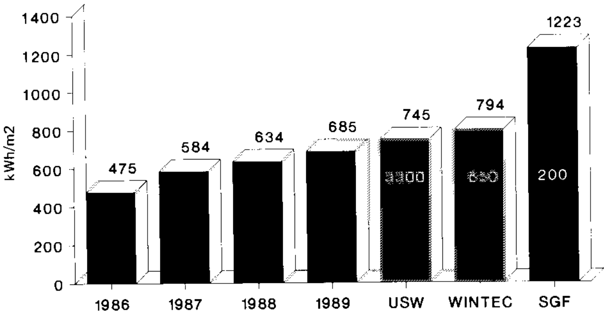

Figure 8. Relative productivity of California wind power plants as measured by kWh/m^2 of rotor swept area.

Notes: The first four bars represent the Statewide average. US Windpower (USW), Wintec, and San Gorgonio Farms (SGF), are some of the best performing wind plant operators. US Windpower operates the world's largerst wind plant: 3 300 turbines in 1989. The 200 turbines at San Gorgino Farms are the world's most productive.
Source: CEC PRS.

mill Owners. (Danish utilities operate additional turbines.) The Danish industry has seen a consistent production improvement since the introduction of the first 55 kW model, a turbine with a rotor 14.5–16 metres in diameter. The improved performance, an increase in generation from 1981 to 1984 of 48%, resulted from improved availability, increasing use of taller towers, increasing swept area relative to turbine rating, improved efficiency, and better siting.[12]

Improved reliability has played a major role in both California and Denmark. During the early years, major failures occurred in half of those turbines installed at any one time in Denmark. The failure rate, though, has rapidly declined. The turbines in the Danish reporting programme are now available for operation from 85% to 80% of the time.

The average performances of all turbines in Denmark is similar to that in California.[13] Danish wind plant at sites with average annual wind speeds of 5.5–7.5 m/second produce about 700 kWh/m^2 of rotor swept area. Because larger machines are showing higher specific yields than their predecessors, yields are expected to reach 800 kWh/m^2 in the early 1990s as newer, more productive turbines are installed. Two small wind plants installed in the mid-1980s at well exposed coastal sites are producing 800–880 kWh/m^2. Several 25-metre diameter turbines on Jutland's west coast are yielding 1 100–1 400 kWh/m^2.

As demonstrated on Denmark's west coast and recently in California as well, intermediate-size turbines (those 25–35 metres in diameter) have now reached the productivity of their small, more proven, counterparts (Figure 9). Most experience with multi-megawatt wind turbines (50–100 metres) suggests that, contrary to the view just a decade ago, intermediate size turbines may be the most cost effective. Up to a point, operators gain savings from increasing rotor size by spreading operation and maintenance costs over greater generation. No more people are required to service a 27-metre turbine than a 15-metre machine, but the bigger turbine captures more than three times more energy.[14] But there are significant diseconomies associated with multi-megawatt turbines and it now appears that overall costs for turbines beyond somewhere in the 30–40 metre diameter range outweigh any projected benefits.

COST OF WIND GENERATION

Recent studies have confirmed the industry's contention that wind energy has become competitive with conventional sources. Typically these studies have assumed that wind plants can be installed for \$1 100–\$1 3000/kW, perform at capacity factors of about 25% and operated and maintained for ¢1–1.4/kWh over 20–30 years. The most important of these are studied by the CEC, PG&E, and the Electric Power Research Institute (EPRI).

The CEC staff has issued two reports on the cost of future generating sources. One examined 'economic' costs only, the second examined economic, environmental and social costs. Wind energy not only leads most alternatives, but it also competes well against conventional sources including coal. Every two years the CEC evaluates some 200 energy technologies, the resulting *Energy Technology Status*

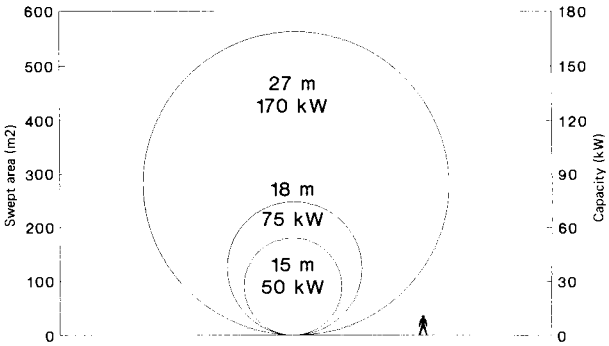

Figure 9. Comparative wind turbines size. Most wind turbines operating in California and Denmark today are 15–18 metres in diameter, or 50–70 kW of capacity if rated conservatively. Most turbines currently being installed are 27–28 metres in diameter.

Source: Paul Gipe and Associates, 1991.

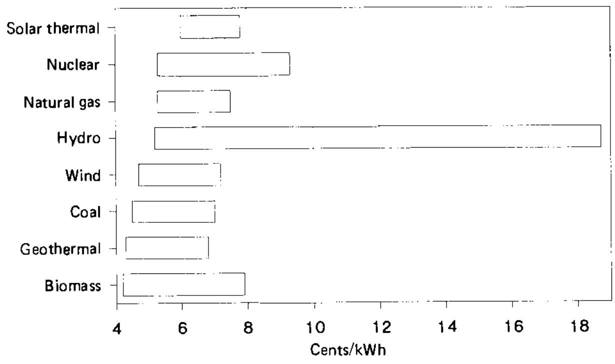

Figure 10. Cost of new electrical generation (constant $1987).

Notes: The estimated cost of new generating sources by investor-owned utilities, levelized over 30 years, in constant US$1987. Though photovoltaics are not shown, the CEC estimated that under similar conditions PV-generation would cost ¢22.7–31.3/kWh.
Source: CEC; 1990 ETSR.

Report reviews the commercial and economic feasibility of each technology. The study then 'provides critical input' into the CEC's energy policy recommendations. The CEC also uses the report when it tests the justification for any new power plant in the State, and, as such, becomes an important reference for the CEC and other State agencies. Because of the State's pivotal role in energy policy, the report also carries weight with Federal agencies and researchers worldwide.

The 1990 Status Report compared the costs of electricity from new generating plants using a variety of technologies, in roles from baseload to peaking, and under various ownership. The staff found that wind plants comparable to those being installed today, when built by investor-owned utilities, could generate electricity for ¢4.7–7.2/kWh over the life of the plant. This includes the cost of capital, operations and maintenance, as well as the cost of replacing major components (Figure 10).[15]

Other studies, both in California and Denmark, are finding similar results. PG&E, the utility serving northern California, estimates that the levelized cost of a new, utility-owned wind plant is about ¢5/kWh in constant dollars.[16] ELSAM, the Danish utility serving western Denmark, expects new wind plants to cost ¢5.3–8/kWh.[17]

Denmark's Risoe National Laboratory found that the levelized cost of a typical 25-metre turbine installed at a good Danish site was 33.4 ore (¢5.6) per kWh. The Danish researchers concluded that wind plants 'can today compete on a purely economic basis with coal-produced electricity.'[18] EPRI, the research arm of US investor-owned utilities, reached a nearly identical conclusion. At good sites 'wind power costs about ¢8/kWh, just about the same as power from more conventional sources.'[19]

Another CEC study examined which technologies are a better buy when social and environmental costs are included. The study by the CEC's R&D office attempted to account for the hidden costs of conventional sources, such as the air pollution from coal-fired power plants.[20] CEC adapted a weighting technique, first developed for land-use planners, to the task. They arbitrarily gave each impact a unitary value to avoid becoming bogged down in determining the degree, or severity of each. The actual numbers are not as important, according to the study, as the realization that social and environmental costs are real, and significant (see Table 1).

Even today, decisions on what kind of power plant to build still depend primarily on price. To gage the effect of 'price' on their results, the CEC boosted the value of price to five times that of the 'social' costs to compensate for any bias against fuels, such as oil and gas, with heavy social and environmental impacts. By weighting the costs of hidden subsidies, pollution, energy security, and waste disposal, as well as the price of the resulting electricity, the CEC found that wind generation costs a fraction of that from oil, nuclear, coal, and natural gas. Even when the importance of price was emphasized, wind – as well as efficiency – was found to come out ahead. The CEC concluded 'that there are certain technologies which remain at the ends of the list in both cases. Oil combustion, nuclear fission, fuel cells, and coal are among the highest cost.' Similarly, efficiency, wind, biomass, hydroelectric, and solar thermal electric

Table 1. Energy technologies highest to lowest economic, social, and environmental cost.

Test case	'Price' case
Oil	Fuel cells
Nuclear	Oil
Coal	Nuclear fission
Natural gas	Coal
Cogeneration	Ocean thermal
Fuel cells	Photovoltaics
Municipal solid waste	Municipal solid waste
Geothermal	Cogeneration
Ocean energy	Geothermal
Hydroelectricity	Solar thermal electric
Photovoltaics	Natural gas
End-use (conservation/solar)	Hydroelectric
Biomass	Biomass
Wind	Wind
Solar thermal electric	End-use (conservation/solar)

Source: M. DeAngelis and S. Rashkin, *Social Benefits and Costs of Electricity Generation and End-Use Technologies*, California Energy Commission, staff report, Sacramento, CA, USA, 1989.

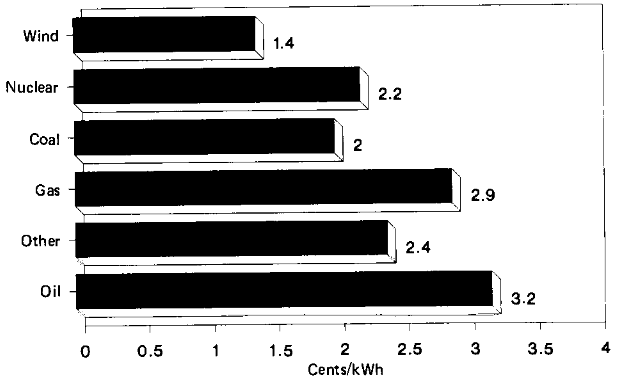

Figure 11. Operation, maintenance, and fuel costs.

Source: Utility Data Institute, Washington, DC, USA; and R. Lynette and Associates, Bellevue, Washington, DC, USA.

'are among the lowest-cost technologies in both case.'

Maintenance costs

Like nuclear power, wind plants are capital intensive and like nuclear the running costs of wind plants should be very low. Wind's proponents have often argued that wind plants would generate electricity inexpensively once the plants were amortized. By 1986 enough operating experience with wind turbines has been gained to determine with some degree of certainty their operations and maintenance costs. The cost to operate and maintain wind plants averages about ¢1.4/kWh.[21] This represents about half the cost to operate, maintain, and provide the fuel for coal-fired and nuclear-power plants, and about one-third the cost of that for oil- and gas-fired plants in the USA (Figure 11).

Unlike other capital-intensive energy technologies, wind plants also require a fair amount of labour. There are currently 1 500–2 000 people permanently employed in California's wind industry. According to the Worldwatch Institute, results from California indicate that wind is the most labour intensive of the energy technologies it examined (Figure 12).[22]

Environmental costs

There are environmental costs to wind plants, principally their aesthetic impact on the landscape, and their noise level on nearby residents. Whether wind turbines are 'noisy' or not is as much a subjective determination as is their aesthetic impact. All wind turbines create unwanted sound – or noise – some to a greater degree than others. The sound of the blades swishing through the air is unique to wind turbines. But there is also the more familiar sound of whirring gears inside the transmission or the hum of the generator.

These sounds are not 'unhealthy' in a technical sense – they do not interfere with normal activities any more than the sounds common in any urban or suburban setting. Nor do they create any significant impact in a technical sense. But they are new, and they are different. People who live in the rural settings where wind turbines are suitable do so because they prefer the peaceful lifestyle of the county to that of the city. Long-time residents are accustomed to the relative quiet of rural life. The addition of new sounds, which people have had little or no part in creating, and from which they receive no direct benefit is disturbing. No matter how insignificant it might be, these new sounds signify an outsider's intrusion. This effect becomes magnified when the source, such as wind turbines, are also visible. Where wind turbines have been seen as an intrustion on an otherwise rural setting, some have objected to them on the grounds of their noise impact.

Of far more importance are concerns about the amount of land required for wind plants and the subsequent effects on the landscape. Critics charge that wind plants require more land than conventional power plants because the energy in the wind is more diffuse than that, say, in coal. The same argument has often been leveled at other sources of solar energy. However, a recent study for the US Department of Energy concluded that, contrary to widespread belief, solar-electric technologies consume no more land than coal or nuclear plants through their entire fuel cycle.

However, wind plants do occuply land (Figure 13). Field experience indicates that wind projects in California occupy about 18 acres (7.1 ha) per MW.[23]

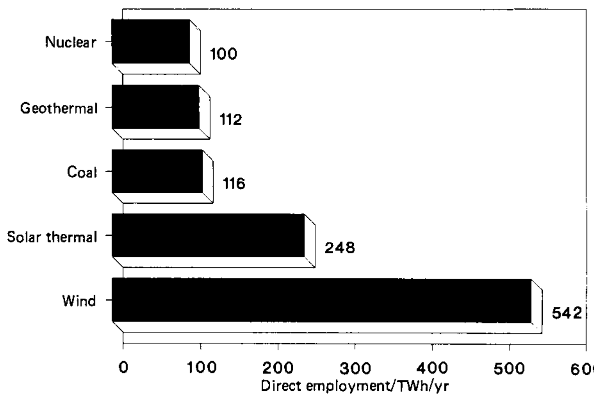

Figure 12. Direct employment from various electricity generating technologies.

Source: Flavin and Lenssen, *op cit*, Ref 22.

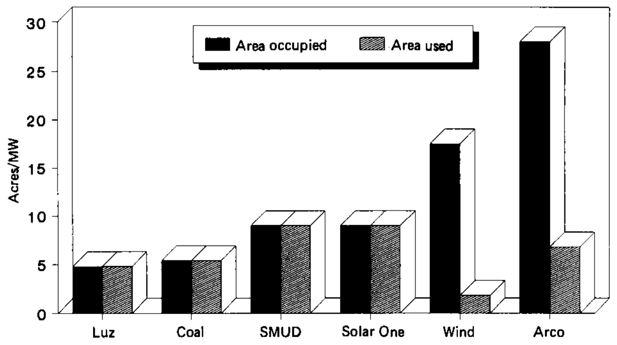

Figure 13. Wind and solar land-use area occupied *v* area used.

Notes: Comparison of the land occupied and used by various electricity generating technologies. Luz = solar parabolic troughs, Kramer Junction, CA, USA. Coal = includes mining; SMUD = two 1 MW photovoltaic plants at the Sacramento Municipal Utility District's Rancho Seco nuclear staion; Solar One = 10 MW central receiver near Barstow, CA, USA; Arco = MW Carizzo Plains photovoltaic plant.
Source: Paul Gipe and Associates, 1991.

The land requirement is slightly greater in Denmark, about 30 acres (12 ha) per MW because of greater spacing between turbines. Wind plants use only a small portion of the land they do occupy typically less than 15%. The US Bureau of Land Management estimates that 10% of the soil on one project monitored was disturbed by the wind plant.[24] In the Altamont Pass, some of the lease agreements between landowners and wind plant operators generally stipulate that no more than 5% of the leased land can be removed from grazing.[25]

European wind plants disturb even less land than those in California. On at least two European wind plants the land is tilled up to the base of the tower and no allowance is made for access roads or even surface expressions of the foundation. When access is needed for heavy equipment, temporary roads are laid over the tilled soil. At the Velling Maersk-Taendpibe plant on the west coast of Jutland only 3.2% of the land is used by the wind plant and most of that is for the roads that were already present when the plant was built.

Public opinion

Regardless of the true impacts of wind technology, whether wind realizes its ultimate potential or not will depend on how people perceive it. In general surveys have found that those who favour wind energy are more likely to find wind's impact on the community acceptable, while those who vehemently object to wind development will oppose it despite mitigation measures.

In a survey of public perceptions of the Altamont Pass, researchers from the University of California at Davis (UC Davis) found that, overall, people agreed that wind projects symbolize 'progress', 'alternative to fossil fuels', and 'use of safe and natural energy'. Those who liked wind energy weighed their symbolic value heavily, whereas those who dislike them responded to more 'basic visual attributes such as conspicuousness, clutter and unattractiveness.' The UC Davis team found that those favouring wind energy 'were willing to forgive the visual intrusion of the turbines on the existing landscape for the presumably higher goal of the project, whereas dislikers were not.'[26]

This 'visual intrusion' elicits the greatest negative response. Though wind plants cause some environmental impacts, the principal impact is clearly visible for all to see. There's no containment building around a wind plant shielding it's inner workings from view. The principal environmental cost of wind energy, when all else is accounted for, is that its visible. Wind turbines cannot be hidden from view. Ironically, this aspect symbolizes wind energy's principal assets: the costs associated with wind energy are not obscured, buried, or shoved off on future generations.

Even a critical study on the potential impact of wind plants in the Los Angeles National Forest found that 'a wind energy development could be a dynamic and exciting addition to the landscape' . . . and would show the public where some of their energy comes from, which would increase public awareness of energy generation, and the costs associated with it.[27]

Whether this visual intrusion is acceptable or not is often determined by whether the viewer sees wind turbines as useful. The effect of spining and non-spinning turbines on the viewer's judgment of 'usefulness' cannot be overemphasized. When the turbines are spinning they're perceived as being beneficial. Even those opposed to wind energy often note that they would moderate their position if the turbines 'worked' more often. Wind turbine's visible operation and non-operation is often perceived by viewer's in terms of reliability. When the turbines are idle, for whatever reason, viewers see wind energy as 'unreliable.' Because the eye is adept at detecting motion, the absence of motion among a mass of wind turbines attracts disproportionate attention. In low winds many turbines will not be spinning because of the wide disparity in the wind from one site to the next. Wind turbines at typical California sites will be in operation only one-half of the time because of the variations in the wind alone.

No where has the question of environmental im-

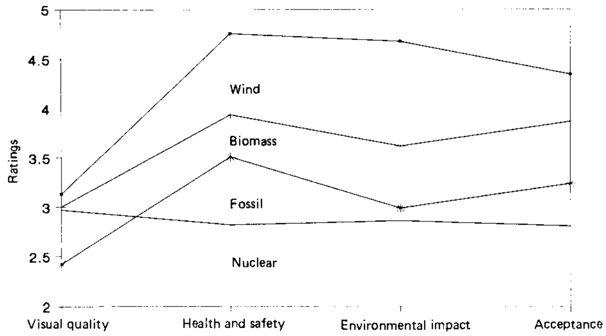

Figure 14. Public preference for various electricity generating technologies.

Notes: Vis. Quality = Visual quality; Hlth & Sfty = Health and safety; Env. Impact = Environmental impact; Accept. = Overal acceptability.
Source: Thayer, *op cit*, Ref 29.

pact from wind energy been more acute than in the San Gorgonio Pass near Palm Springs. The area is the scene of the most protracted, bitter, and well-known controversy over the value of wind energy. The consequences of the controversy there have been far reaching, not so much for the numbers of people involved, but because of their celebrity status, and political influence. The situation is somewhat reminiscent of the furore surrounding the Eiffel Tower. Though no famous writers or artists are involved as in the Paris of 1889, they've been replaced by Southern California's equivalent: retired entertainers and powerful ex-presidents.

Thus the stage for the most telling public opinion survey conducted to date. Performed by contractors to Riverside County in 1986, the telephone survey, because of its conclusions, remains controversial to this day. All of those surveyed were from Palm Springs and the small communities nearby. Most (58%) lived within two miles of the wind turbines, the remainder lived 2 to 5 miles away. Of those within two miles, three-fourths could see the turbines.

The results shocked wind's critics as well as some elected officials who had staked their political careers on fighting wind turbine 'blight'. The survey found most residents (50%) ambivalent on whether the wind turbines were worth the environmental costs, 24% said they were not, and 22% said they were. Nearly three-fourths said that the wind plants had not degraded the environment around their homes. On the question of aesthetics, 'there was a fairly even distribution of opinion.'[28] Because noise is a function of distance, those nearest the turbines should find them noisier than those who lived some distance away. The survey concluded that this was indeed the case. Yet two-thirds said that the noise from the turbines 'did not disturb them, while 11% indicated that it did.'

The results of a mail survey in northern California is revealing because of the light it sheds on the NIMBY response.[29] The researchers polled public reaction to four energy technologies – biomass, nuclear, fossil, and wind – and where people would find them most acceptable. The survey identified NIMBYs as those who found a technology 'acceptable' in their country, though they would not accept it within five miles of their homes. Most of those surveyed found wind desirable – somewhere. Only 2% thought wind plants were completely unacceptable whereas opinion was more polarized about nuclear and fossil fuels. One-fourth found fossil-fired plants unacceptable in the county, and one-third found nuclear plants unacceptable. But wind drew the greatest NIMBY response.

According to Thayer,[30] this survey and others he has conducted in northern California, show the public ambivalent towards the aesthetic impact of wind turbines. On the one hand wind is an energy technology preferred by most respondents, yet the visual impact from non-spinning turbines is troubling. Despite this, Thayer's team found wind plants the preferred power source of the four considered. People were willing to accept wind plants closer to their homes (within 2–5 miles) than any of the other technologies. In contrast, the minimal acceptable distance to a nuclear power plant was 20–100 miles.

Surprisingly, of the six factors Thayer measured – health and safety, reliability, environmental impacts, cost, dependence on foreign oil, and visual impacts – wind energy's presumed Achilles heel, visual impact, was the least important. Though there was more disagreement about wind's visual costs than that of the other technologies, wind still received the highest rating of visual acceptability of all the plants, including nuclear (Figure 14). The respondents were also more willing to view wind plants from highways, parks, and their offices than the other technologies, though all agreed that parks were the least desirable place from which to view any of the plants. Not unexpectedly Thayer notes that 'most people would prefer no development of any type of energy development if given the choice.'

POTENTIAL FOR WIND IN THE USA

Currently wind energy produces only 0.1% of the nation's electricity, but it could produce a significantly greater amount during the next decade. The

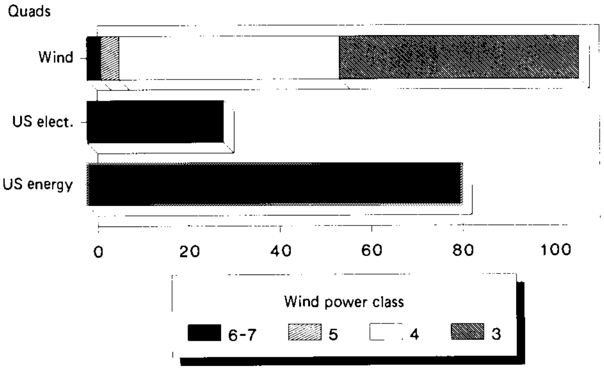

Figure 15. Wind energy's potential contribution to US electricity and energy supply under moderate environmental restrictions (1990).

Notes: Wind Power Class 6–7 = >8 m/second average annual wind speed; Class 5 = 7.6–8 m/second; Class 4 = 7–7.5 m/second; Class 3 = 6.4–7 m/second.
Source: Battelle, *op cit*, Ref 33.

US Department of Energy estimates that by the year 2000 wind – with business as usual – could supply 10 times more electricity than produced in California today.[31] Even in California there remains ample undeveloped wind resources. The CEC has identified more than 7 000 MW of prime wind resources, only a portion of which has been developed.[32]

The Great Plains contain tremendous potential. One ridge in southwestern Minnesota alone could produce as much wind-generated electricity as that produced in all of California today. And just one site in Montana could provide 17 times California's current wind generation. Battelle Pacific Northwest Laboratories, in a recent report, calculates that there are sufficient wind resources in the contiguous USA to meet 27% of the nation's electrical consumption even after removing many areas because of potential land-use conflicts. Battelle's study assumed the ability to ecnomomically-use only class 5 (7.5–8 m/second annual average wind speed) or windier resources, under moderate environmental restrictions (Figure 15).[33] But Class 4 (7–7.5 m/second) resources are currently being used in Denmark and Germany. If Class 4 resources were tapped in the USA, wind alone could meet the nation's total demand for electricity. In a realistic scenario, wind energy could meet 10% of the nation's electricity supply sometime after the year 2000.

CONCLUSION

Wind energy has come of age during the past decade. The success of wind energy in California and Denmark has proven that the technology has matured, that is as reliable as conventional technology, and that it's economically competitive. Furthermore, surveys have shown that the public is not only willing to accept its visual impact, but prefers wind energy over competitive technologies when given a choice. And there are sufficient wind resources in California and elsewhere in the USA for wind energy to ultimately make a significant contribution to electric supply.

The views expressed here are those of the author and do not necessarily represent those of any organization with which he may be associated.

[1]World ranking depends upon the value of the US dollar. As the dollar slides California slides to seventh place.
[2]Wind power plants are also known as wind farms. They are sometimes, incorrectly, identified as 'wind parks.' Arrays of wind turbines are not parks, but a collection of generating units like those found in any other power plant.
[3]Wind turbines provided about 2.5% of Denmark's generation in 1990.
[4]Charles Imbrecht, California Energy Commission, Address before the Annual Conference of the American Wind Energy Association, San Francisco, CA, USA, September 1989.
[5]G. Maneatis, president, Pacific Gas & Electric Co, described California's wind power plants as the 'most successful of the alternative sources of energy' in a statement at RETSIE 1989, 21 June 1989, Santa Clara, CA, USA.
[6]David Roe, *Dynamos and Virgins*, Random House, New York, NY, USA, 1984.
[7]Sam Rashkin, California Energy Commission, *Wind Project Performance Reporting System*, annual reports from 1986 through 1989.
[8]California Energy Commission, *1990 Electricity Supply Report*, Sacramento, CA, USA, 1990.
[9]US Windpower (USW) now operates 4 000 wind turbines in northern California. Nearly all of these turbines are USW model 56–100, a 100 kW, three-bladed, downwind machine nominally 18 metres in diameter.
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Chapter 5

Ocean Wave Energy

Johannes Falnes and Jørgen Løvseth

Ocean waves may potentially contribute one TW to global energy supply. The time variability of wave energy can be smoothed by integration with the general energy supply system. Many different wave power plants, some of them multi-purpose, have been proposed, assessed, and cost estimated. After a subsidized introductory phase, wave energy is expected to be economically competitive, helped by the development of new designs and technical improvements, and by historically established experience. Only slight environmental impact is expected. Operation and maintenance may mean an economic boost to coastal societies.

Keywords: Wave energy; Renewable energy; Coastal development

The present global flux of commercial energy through our societies is about 10 TW (1 TW = 10^{12} W). Per capita, the value is about 2 kW on average, but a factor of 2 to 5 higher, however, in the rich countries. The global population is expected to rise by at least a factor of 2, before a stabilization, and it is a desirable goal that all people should have a good standard of living. If every member of the future world were to consume as much energy as present 'well-to-do' people in the rich countries, this would mean an increase by a factor of 4 to 10 in future global energy-use.

Bearing in mind that some 80% of today's global energy flux originates from fossil fuels, and that a stabilization of the CO_2 content of the atmosphere at the present level means that the burning of the fossil fuels should be reduced by a factor of 1/3, one realizes that global society faces a severe challenge. Even if more efficient use of energy resources and energy conservation are included in any future energy strategy, there will nevertheless be a demand for energy which will be hard to meet in an environmentally satisfactory way. But 'hi-tech' utilization of renewable energy resources (including solar and geothermal) does, in our opinion, offer the possibility of satisfying future energy demands in an acceptable way, provided that:

(1) A vigorous development programme is started by the industrialized countries; and,
(2) the developing countries are given free access to the new technology to tap the natural energy fluxes.

As well as water (hydro) energy and wind energy, wave energy is also naturally available as mechanical energy. In principle, it can therefore be converted rather efficiently to electricity. As electrical power and a strong electrical grid are, at present, a fundamental part of the infrastructure in all industrialized countries, our main interest in this paper will be conversion of wave power to electricity for general use on the public grid, although in the future conversion of wave energy to hydrogen energy might be an interesting option. With these long-range goals in mind one should not, however, forget that wave energy must first be commercialized (and indeed, is already being so) for various applications of energy-use on a more modest scale.

DIVERSITY OF WAVE-ENERGY CONVERTERS

In the patent literature there are more than a thousand different proposals for utilization of wave energy. Wave-power devices, on or beneath the surface of the ocean, may include fixed (shore-based or bottom-standing) structures, floating structures, pneumatic chambers, or oscillating and moving parts. Some types of wave-energy converters (WECs) are illustrated schematically in Figure 1. More information may be found in some review papers on theoretical matters[1] and on practical problems[2,3] associated with wave-energy conversion.

Various wave-power production units with power levels up to several hundred kilowatts are, at pre-

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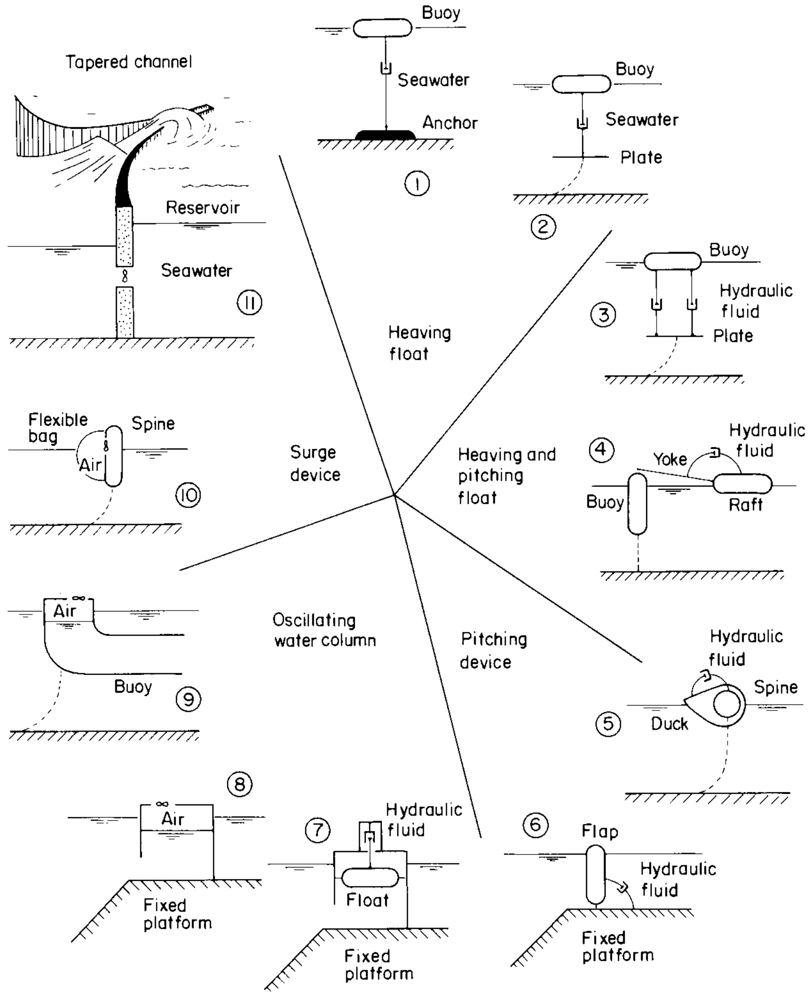

Figure 1. Schematic representations of various types of wave energy converters.

Source: Hagerman and Heller, *op cit*, Ref 2.
Notes: With some types (1–7) the motion of oscillating bodies is utilized to convert energy by means of hydraulic pumps, and with other types (8–10) the pumping action of oscillating water surfaces is utilized to run air turbines. In the last example (11) the height of the wave increases as it runs into a shore-based, horizontal tapered channel, where it spills over into an elevated reservoir, creating head for a water turbine.

sent, planned, under construction, or being tested in several Asian and European countries: China, Denmark, India, Japan, Norway, Portugal (Azores), and the UK (Scotland). Most of them are of the oscillating-water-column type in a fixed structure (Figure 1, case 8) on a steep rocky shore, in a breakwater or in a caisson. A Norwegian company, NORWAVE AS, is planning to construct commercial wave-power plants of the tapered-channel type (Figure 1, case 11) in Indonesia and in Tasmania.

Although on-shore WECs have the advantage that access to and operation of the plant are easy, they have some drawbacks. Suitable locations may be rather rare, and civil engineering work is difficult on a wave-exposed shore.

Off-shore, available wave power may be substantially larger than on-shore, and possible locations for installation are less restricted. Another advantage is that off-shore WECs represent less visual impact, as seen from the land. Access and operation are more difficult, but construction (in a shipyard) may be relatively easy. Submerged WECs, which utilize the wave action just below the ocean surface, are even less accessible for maintenance, but they have the additional advantage of being less exposed to corrosion and to extreme wave forces.

Converted wave energy may be used for various purposes. In addition to electricity production for delivery to a grid or for local use, wave energy converted to hydraulic energy may be used for desalination of sea water or for running refrigeration plants. These purposes may be of great importance for many coastal and island communities. Energy for pumping or heating sea water would be of interest for many fish farms. An additional purpose of wave-power converters may be to serve as break-waters to increase the weather window for certain on-shore or off-shore operations, to increase the season for beach recreation activities, or to reduce coastal erosion, which is a problem in many places. Another possible use of wave energy is for the propulsion of vessels. In the future, wave energy may be exploited on the open oceans by floating, energy-consuming factories, producing, for instance, hydrogen for a world which utilizes clean energy in larger amounts than at present.

THE NATURE OF WAVE ENERGY

Ocean waves are generated by blowing winds. Sea swells transport energy from storm centres to distant shores. Statistical observations of real seas have been made at various ocean sites. From these data it is possible to provide estimates of available natural wave energy in various oceanic regions around the world.

The natural power transport J per unit width of the progressing wave crest has a typical average value of $J = 50$ to 100 kW/m on the open ocean at latitudes of 40° to 65°, and the value decreases as the poles or the equator is approached. In tropical regions $J = 10$ to 20 kW/m is a more typical average value.

The global energy potential represented by waves hitting all coasts may be estimated to be of the same order of magnitude as the world's present electricity production, approximately 1 TW. (This figure also represents an estimate of global economic hydro-power potential, of which about one-fifth has been developed.) If wave energy is harvested on the open oceans, energy which is otherwise lost in wave breaking and friction can be utilized. On the lee side of the WECs the winds blowing over a certain fetch length will be able to generate new wave energy. The corresponding global natural power potential is estimated to be more than 10 TW, that is, of the same order of magnitude as the total present-day energy consumption.

The annual average of the wave power transport J may vary from one year to the next. There are also seasonal variations. For the most part, the variability of real ocean waves represents a problem for wave energy utilizations. However, in the northern oceans of the world, most of the wave energy is generally available in the winter season, which provides a seasonal advantage.

The average wave energy can fluctuate by a factor of 10 from one week to the next. The wave power during a storm can be five times higher than the mean value for the week the storm occurs. On the timescale of minutes, or fractions of minutes, the wave power during wave groups may be of the order of 50 times the wave power between wave groups. For this reason it is advantageous that WECs are equipped with an energy storage system to even out the short-time fluctuations and allow for a better duty factor in terms of the installed power for the individual WEC. By operation of groups of WECs in parallel, the short time fluctuation in the power delivered to the grid will be evened out.

The wave power is usually larger in open oceans than in sea regions of lesser extent, or in regions which are in some way shielded from the waves of the open ocean. For instance, the mean wave power is smaller in the North Sea than in the Atlantic Ocean off the west coast of the British Isles.

Usually, the mean wave power transport is reduced as the coast is approached. As the water depth decreases, energy is lost by friction at the sea bed and wave breaking occurs on shallow water. Moreover, wind blowing from the land-side does not create large waves near the coast. When there is wave action at the sea bed, the bottom topography causes refraction of the waves. This, in turn, produces defocusing in some regions, while there is natural wave amplification (focusing) in other areas. This depends on wave frequency as well as on direction of wave incidence. If one averages over all frequencies and all directions, one may still find areas near land which are better locations for wave-power devices than other areas.

Note that the power output, and hence, the economic value, is related to the average wave power transport, while the design criteria, and hence the necessary investment in construction, are related to the extreme wave situation. Hence, it is advantageous to choose a location where extreme waves are reduced relatively more than the smaller average waves.

COST ESTIMATES AND PRESENT TECHNOLOGY STATE

Several different WECs have been assessed technically and economically as part of national wave energy research programmes since the late 1970s.

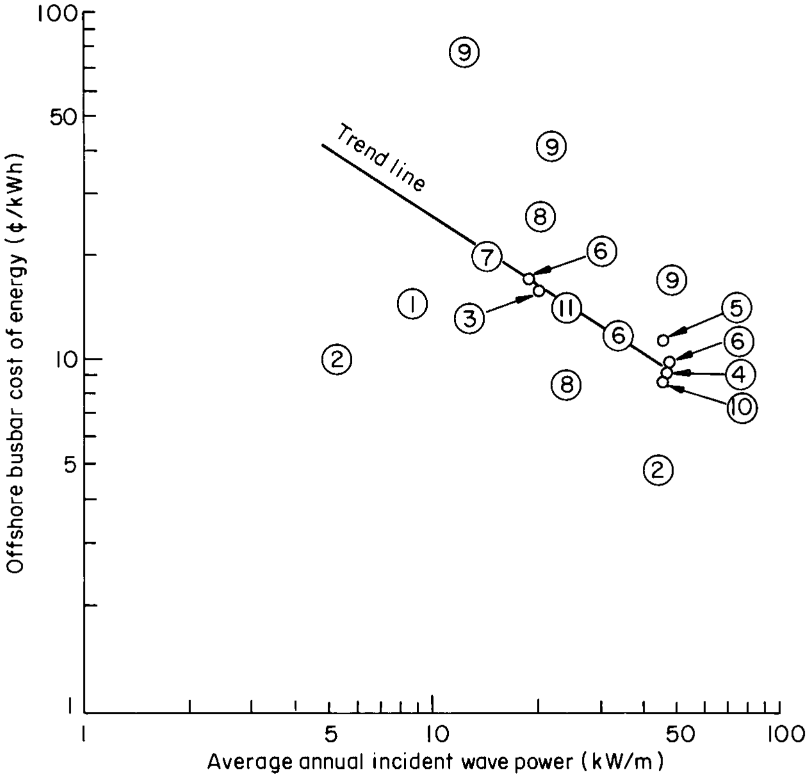

Figure 2. Assessed cost (see Hagerman and Heller, *op cit*, Ref 2) of converted wave energy delivered to the electric grid from 11 different types of WECs.

Source: Reproduced from Hagerman and Heller, *op cit*, Ref 2.
Notes: The 11 types of WECs (see Figure 1) are plotted as a function of the average natural wave power transport *J* at the chosen location of the proposed wave power plant. The data given in this double-logarithmic graph seem to fit, approximately, to a descending straight line as shown.

For instance, four proposals studied in the British programme were estimated (in 1978) to give an electricity cost in the range of p36 to p56/kWh. In 1982, cost estimates in the range of p3 to p16/kWh were found for seven different WECs. This reduction reflects new ideas and better technical solutions and represents a significant research achievement. Similar reduction was also seen in other national research programmes. Three proposals assessed in Norway in 1981 came up with cost figures of NOK 2.5 to 4.9 (20 to 40 pence) per kWh; a new assessment a few months later, with improved designs of essentially the same proposals, gave reduced numbers of NOK 1.2 to 1.4 (10 to 12 pence) per kWh. The higher costs from Norway relative to the UK, reflect both higher production costs and higher interest rates in Norway.

A more recent estimate[4] evaluates various types of WECs developed by 12 different companies in eight countries. Costs in 1987 are given in US$. Estimates of the offshore capital cost per kW of installed electrical power vary between $580 and $4 830. The annual cost for operation and maintenance is assumed to be a figure between 0.4% and 8%, where a lower value may be expected, typically, for a system of relatively few moving parts, but with greater expenditure of steel and concrete, and hence, higher capital cost. Capacity factors (annual duty factors) between 13% and 60% were assumed. Of the 12 plants considered, the lowest and highest plant sizes were of 0.35 MW and 2 000 MW installed electrical power capacity. The average wave power transport of the envisaged plant location was between 9 and 50 kW/m. Further assumptions in the cost estimate were a discount rate of 12.5%, zero inflation, 40% income tax, and a lifetime of 30 years. For most of the assessed WECs the calculated cost of energy is between $0.08 and $0.25/kWh (Figure 2). The results indicate a trend that the logarithm of the cost of energy decreases linearly with the logarithm of the incident average wave power transport *J*. Most of the examined systems appear to fit approximately a line between ¢10/kWh at J = 50 kW/m and ¢20/kWh at J = 20 kW/m.

Note that the above cost estimates are not based upon practical experience from wave power plant operation. Two Norwegian companies have a few years experience of testing on-shore demonstration WECs of some 100 kW in size, but these companies have not yet published data from their operational experience.

One of these companies (Kvaerner) had plans to construct a wave power plant of the oscillating water type (Figure 1, case 8) in Tonga, South Pacific. But due to an internal reorganization, the company decided in 1990 to shelve its wave energy activity. A similar WEC is at present under construction off the Trivandrum coast, by the Indian Institute of Technology in Madras. This latter project, contrary to the shelved Norwegian project, benefits economically from inexpensive labour in India. Some wave power converter units on-shore, on a breakwater, or closely adjacent to a breakwater have already been tested. These units are typically characterized by few moving parts, and by relatively large concrete structures. Already it seems that such systems are going to be commercial in the 1990s in developing countries where knowledge, skill and inexpensive labour are available, as for instance in China and India. Moreover, on-shore wave energy units will, within a few years, deliver commercial energy to small island and coastal communities, which at present have to rely on expensive diesel electricity.

FUTURE PROSPECTS

For large-scale energy supply for coastal industrialized countries, off-shore WECs will be needed, and the present, previously-mentioned simple large-structure WECs do not look like becoming commercial within the next few years. But we believe that after more R&D wave energy may make an important contribution to energy supply in the next century. Later we shall give some arguments for this belief. It should be remembered wave power utilization is a relatively new research subject.

All technologies show a decrease of cost per unit produced, as a result of experience gained, and of more economic methods of production. A typical trend is an inflation-corrected unit cost reduction of about 20% to 25% for each doubling of the cumulative production volume. These numbers apply, respectively for production of coal and electricity in the USA.[5] However, for computer technology, casual observation indicates that the typical rate of cost reduction has been some 50% per doubling of the cumulative production.

Although the technical components used in WECs are mostly well-known, the combination is new. Assume, from the previously mentioned assessment,[6] that a prototype wave-power plant of, say, 100 MW capacity will deliver electricity at a cost of ¢20/kWh. If technological experience results in a 20% cost reduction for each doubling of cumulative production, an energy cost of ¢5/kWh will result before wave power plants of capacity totalling 10 GW have been reached. This cost is certainly competitive, but in order to reach this goal, much financial support is required during the less competitive phase of the technological development.

In some national wave energy research programmes around 1980, the envisaged devices were designed to convert a maximum of the natural energy incident on a coastline. Since the natural energy is free, this is not necessarily the most economical design strategy. Rather, the installed power capacity relative to the average wave power should be left as a free parameter in an economical optimization. This strategy might give a reduced annual production, but a higher duty factor and, hopefully, a better economy. The need for an energy storage system in the primary wave energy converting step, in order to even out the short period fluctuations discussed previously, would be reduced with this strategy, and should be evaluated as part of the economic optimization.

This design philosophy has not been much utilized in the rather simple types of WECs tested in the sea so far. The strategy requires more sophisticated designs, where special mechanical components are needed. Here is a challenge for inventors, scientists and designers working with mechanical engineering. Only very few research teams from within this branch of technology have, up till now, been engaged in the R&D of WECs.

Most of the rather simple WECs built so far are essentially civil engineering structures. This may be an advantage if wave power plants are to be constructed in non-industrialized countries. But a drawback is that a relatively large expenditure of steel and concrete is required. For a more advanced wave-power technology, where a better ratio between material expenditure and converted wave power is attained, it is necessary to develop electronic control units and new mechanical components, such as pumps, valves, hydraulic motors and turbines. This advanced wave power technology will also require local expertise for operation and maintenance of the WECs.

An off-shore power plant may consist of hundreds or even thousands of equal WEC units, each having a power capacity of, typically, a few hundred kilowatts. WEC production may thus be serialized, which will reduce costs. Energy from the individual units may be collected as electrical energy by cables from generators inside buoys or from generators placed in housings on the sea bed below the primary wave energy converters. Otherwise energy from individual units may be collected as pneumatic energy as with the British 'Clam' device (indicated in Figure 1, case 10). Alternatively, hydraulic energy in the form of pressurized sea water may, through collecting pipes, be transferred from many power buoys (of the type indicated in Figure 1, case 2) to a common turbine-and-generator unit of installed power capacity typically in the region 10 to 100 MW.

POWER FROM WAVES TO THE ELECTRIC GRID

Power from WECs must be produced when incoming waves are available, and this does not generally match consumer's electrical power demand. It is, therefore, necessary that other types of energy sources are also available. For small island and costal communities relying on diesel power for their electricity supply, combination with wave power is a potentially attractive option.

In larger communities, with many WECs positioned at various places off the coast and connected to the same grid, some of the variations will even out. We will take as a basic assumption that the power grid is strong, and international rather than national. Other resources on the grid will then be able to compensate for the variability of wave energy on the local scale. In a large grid, even part of the weather variations in the WECs output will average out. If there are solar power stations on the grid, it is likely that the output from these stations will show variations with an opposite phase to the wave power output, both with respect to weather and seasonal variations. A detailed discussion of this problem will depend on the resources and users connected to the grid.[7]

If the Norwegian situation is taken as an example, in the future we will probably have a grid dominated by hydropower supply, as we have today, but in addition we may get power from wind and wave energy. The two latter will vary in phase for part of the time, but wind energy will also be available in periods with wind direction from land-to-ocean, and wave energy will last a day or so into a quiet period. The national grid is already connected between Denmark and Sweden, where we will probably also find wave and wind energy converters. Over Scandinavia, there will be a considerable averaging effect. With respect to seasonal variation, both wind and wave power will have a phase opposite to that of hydropower. Wind and wave energy peak in early winter, when the precipitation normally appears as snow; hydropower peaks when the snow is melting in spring and early summer (in the mountains). Water is stored in basins to be used the following winter. Electricity demand peaks in the winter, and this will be ever more the case if all heating is achieved by heatpumps driven by electricity during the midwinter period. Solar heating will be feasible spring, summer and fall.

The residual weather variations in a strong grid due to a large contribution of wave (and wind) energy from an extended geographical area, will be very gentle, and to a large extent predictable. The backup problem with nuclear energy is in fact more severe, since the failure of one plant may imply that 1 GW has to be replaced with no warning. An advantage of the established Scandinavian hydropower grid is a large generating capacity compared to the normal load, this is to even out seasonal variations between the various districts, and to establish a large regulatory capacity.

ENVIRONMENTAL CONFLICTS WITH EXISTING ACTIVITIES

Waves represent a clean source of energy. But utilization of this source of energy will, of course, have some environmental and political impacts, some of which we shall discuss.

Distant off-shore WECs have very little visual impact as seen from land. In contrast to moored off-shore WECs, plants on-shore require some irreversible encroachment of the land topography.

The WECs will damp the waves by extracting energy. This will give a sheltering effect. For a buoy power plant sheltering may, however, hardly be noticeable on-shore in the case of large waves, due to the limited power capacity and other nonlinear effects of the WECs. Thus the ecological cleaning effect caused by the heaviest waves will still exist. Whether the general damping of the wave energy will have any ecological effect is not known to us, and will have to be investigated as part of the development programme. If the wave power plant is intentionally combined with a breakwater, the sheltering is certainly more significant, which may be important for reduction of shore erosion, or for increasing the season for certain technical operations or beach recreation activities.

For the traffic of small boats, the sheltering effect will in most cases be beneficial, and will probably compensate for the risk of collision with the buoys. Heavier ships will probably find the buoys a nuisance, and openings in the rows of WECs to provide satisfactory lanes for commercial shipping traffic must be established. The position of the WECs should be included in the new digital map system of the seas which is being established, and together with suitable regulations, the potential problems for traditional seabound traffic should then be minimal. As an advantage to shipping traffic, the WEC units could be equipped with navigation lights and identification.

Judging from reactions to off-shore oil activities, fishermen will perhaps not welcome the rows of off-shore WEC units. From the point of view of the fish, the WECs will, however, create a safe zone, and one might argue that fish right now are more in need of protection. From a serious point of view, there is a potential conflict with some traditional ways of fishing, and this problem must be resolved. But overfishing has been the real problem along the coasts of the developed nations, resulting in strict regulations on the allowed catch. A zoning procedure, where part of the continental shelf is reserved for WECs, will not reduce the total amount of fish caught. At present, and in the future, the limited quota of fish is the real problem, and not the space available to fish. A peaceful coexistence between the activities of harvesting the fish and wave energy will therefore undoubtedly be possible.

For fish farming, which is becoming as important as the natural fisheries in some regions, WECs will probably be an advantage, because of the general damping of the waves, which will reduce the wear on the installation, and facilitate daily operation.

As discussed later, development of wave power will mean a much needed new activity in some coastal regions, and conflict with traditional activities must be handled in this light.

In connection with off-shore oil activity, littering of the sea floor has been a problem. Strict regulation to avoid such unnecessary problems in the development of wave energy must, of course, be applied.

POLITICAL CONSIDERATIONS AND CHALLENGES

The building of WECs for off-shore installation will provide suitable employment for shipyards worldwide. Since the resource is free, the initial capital cost will correspond to the production and installation cost of the equipment. Both the initial production and the subsequent operation will be labour intensive and will, thus, generate new jobs, which will be welcomed in most countries.

The installation and operation of off-shore WECs will offer new opportunities for employment in coastal populations. This will be beneficial, as the industrialization of the fisheries has left these areas in a miserable state. Most of the present activities which exist in coastal regions in industrialized countries have some kind of subsidies or protection. For strategic, security and defence purposes, most countries are willing to pay something to have a basic level of population and business activity in these regions. New meaningful activities, such as the harvesting of wave and wind energy, will therefore serve a multitude of purposes, in addition to providing pollution free energy from a non-depletable resource base.

To get a feeling for the scope of the operational activities, we present some numbers. For a well-exposed coast, with an efficient WEC system, 25–40 kW/m of electric energy could be harvested. This will mean 10^{10} kWh/year (10 TWh/year) per 30–45 km of coastline. With an electricity price of ¢5/kWh, and some 10% of the yearly income being spent on operations traceable to local activities, this amounts to an annual income of some $50 million, or more than $1 million/year/km of coastline, which is a considerable amount for these regions, even if we scale down by a factor of 2.

For coastal countries which at present depend greatly on imported energy, it may be of some strategic importance if their wave energy could be utilized. Before wave energy can be technically exploited on the open oceans (eg for hydrogen production), international agreements and regulations will have to be drawn up. Who has the property rights of this source of energy? This is not an easily solvable problem. Note that the swells arriving at the beaches of a country, may originate from storms thousands of kilometres away. There may be a potential conflict if another country exploits the waves in international waters before the swells reach wave power plants in territorial waters.

INSTITUTIONAL INERTIA AND PSYCHOLOGICAL FACTORS

Most of the expenditures for energy R&D in the post-war years have been spent on nuclear energy. In most countries, this alternative has been rejected by the general public. In addition, safe installations, with satisfactory provisions for waste disposal, have turned out to be very costly. After more than 40 years with annual budgets of the order of $1 000 million, fusion research has yet to provide a credible proposal for a reactor that will produce more electricity than it consumes. Despite these facts, nuclear programmes still receive the lion's share of energy R&D money in most of the developed countries. A great deal of prestige and funds have been invested to create weighty institutions, which now seem to be running largely by their own inertia.

There seem to be psychological barriers against investing comparable amounts of money to utilize the everyday phenomena of solar radiation, wind and wave energy. The research that has been completed on these renewable resources clearly demonstrates that they, together with energy conservation technologies, can provide the equivalent of the present energy-use of rich populations for the *whole* of the future world population.

In order to attain eventual economic competitivity in a free market, a development programme must be started in the nations with good resources. Such a programme must have a budget comparable to that spent on nuclear energy. Although one might argue that the technology involved is not basically new, the problems involved in installation and operation of offshore WECs needed for a significant contribution to the world's energy supply, will require a heavy development programme. As the prospective output of electricity for the nations involved is comparable to that of the nuclear programmes, the R&D effort must also be expected to be comparable. Because of the smaller units involved, WEC's promise a greater potential for cost reduction by serial and volume production than nuclear installations.

If the cost reduction by experience and volume production is taken into account, we are left with the conclusion that the economic prospects for wave energy, as for several of the other renewables, do look bright, provided a heavy developmental programme comparable in scope with the nuclear programme is started. Yet both the political and technological establishment seem to lack the courage to start such programmes. It seems easier to make a start on projects concerned with more 'exotic' problems, such as fusion and star wars rather than every day phenomena. The fundamental reason for this may be the risk of failure – if an exotic process is involved, one can always blame the unknown features: where everyday phenomena is concerned, this is not so easy.

CONCLUSION

The proposed development of off-shore WECs could make a substantial contribution (of order of magnitude 10^{11}–10^{12} W) of electricity from renewable resources. The environmental problems are seen as rather minimal. Minor conflicts with fishing communities are conceivable, but this must be weighed against the economic boost such a development could have on coastal areas.

A very strong R&D programme would be needed to achieve significant utilization and should be based on extensive international collaboration. During the introduction period of wave energy, subsidies will be needed. But in the final stages, the installation of off-shore WECs is expected to be profitable in competition with other alternatives, renewable as well as non-renewable.

If wave energy is, in the future, exploited on the open oceans, for instance for the production of hydrogen, certain international regulations are desirable and necessary in order to avoid potential conflicts between nations.

[1]D.V. Evans, 'Power from water waves', *Annual Review of Fluid Mechanics*, Vol 13, 1981, pp 157–187.
[2]G.M. Hagerman and T. Heller, 'Wave energy: a survey of twelve near-term technologies', *Proceedings of the International Renewable Energy Conference*, Honolulu, Hawaii, 18–24 September 1988, pp 98–110.
[3]S.H. Salter, 'World progress in wave energy – 1988', *International Journal of Ambient Energy*, Vol 10, January 1989, pp 3–24.
[4]Hagerman and Heller, *op cit*, Ref 2.
[5]J.C. Fisher, *Energy Crisis in Perspective*, John Wiley, New York, USA, 1974.
[6]*Ibid*.
[7]Hagerman and Heller, *op cit*, Ref 2.

Chapter 6

Hydroelectric Energy

Geoffrey P. Sims

The paper discusses the nature of hydroelectric energy and how it is integrated into modern power systems. The role of tidal power and pumped storage schemes are mentioned briefly. The principal constraints to the wider development of hydropower are concerned with their effect on the environment, their high initial cost, and uncertainty over the future price of oil. These constraints are discussed, together with brief mention of how the challenge each represents is being countered. Representative recent technical advances, particularly in the civil engineering field, are described. The paper concludes with a brief account of some of the institutional problems encountered in promoting hydroelectric projects, particularly those where more than one country is involved.

Keywords: Renewable energy; Hydroelectric energy; Hydropower

Hydroelectric power is derived from harnessing the power released when water passes through a vertical distance usually referred to as the 'head'. Hydropower has its origins in the pre-industrial revolution technology of water wheels and is simple in concept. The power generated is proportional to the product of flow and head. Projects in mountainous terrain typically run under a high head, perhaps over 1 000 metres, which for a given output requires a small flow of water. Projects on large flat rivers, on the other hand, are arranged to pass a large flow of water through a small head of a few metres. The distinction between small- and large-hydro is arbitrary: the same concept and basically the same technology apply for installations of 1 kW and 10 GW. Economies of scale are available;[1] small schemes are more expensive per installed kW but this is counteracted to some extent by their being simpler in design and layout.

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Hydroelectric power is also generated in pumped storage schemes such as the 360 MW Ffestiniog Project or the 1 800 MW Dinorwig Project in Wales. Here the basic principle is that two reservoirs are formed, one at a higher level. When water flows from the upper to lower reservoir power is generated by the turbines. When there is spare generating capacity on the system water can be pumped, sometimes simply by reversing the turbines, from the lower reservoir. Pumped storage schemes are the only practicable means of storing electrical energy in commercial amounts.

Tidal power is another valuable manifestation of hydropower. A barrage is constructed across a tidal estuary such as that at La Rance in northern France. Sluices and turbines are arranged so that power can be generated from water flowing from high tide level outside the barrier to a lower level inside. As the tide falls outside the barrier there comes a time when the level inside is higher than that outside, when power can again be generated from water flowing to the lower level.

Other factors being equal, a large hydro scheme is preferred because the unit cost is lower than for small projects. Not infrequently, large dams are proposed as part of a large scheme not only to create the necessary head but also the associated water storage which improves the reliability of electrical output. Most of the postulated adverse environmental impact of large-scale hydro schemes is associated with these high dams and their extensive reservoirs. Smaller schemes have basic structures and little storage.

The International Commission on Large Dams (ICOLD) is a significant organization sharing knowledge of the design, construction and behaviour of large dams. It is therefore concerned with many of the features of large hydroelectric schemes. Currently ICOLD committees are working on many subjects including: environmental effects; aging behaviour; and technical advances including computational methods and new construction methods.

This paper makes no attempt at an exhaustive approach to the subject. In the space available, the salient features of the technology, the major con-

Table 1. World hydropower potential.

Region	Exploitable resource (GW)	Installed capacity (GW)	Percentage of resource exploited (%)
North America	184	153	83
Central America	66	11	17
South America	398	105	26
West Europe	118	116	98
East Europe	663	90	14
Middle East	68	22	32
Africa	225	18	8
Asia	513	82	36
Pacific Rim	224	40	18
Australasia	35	13	37

Source: WEC, *op cit*, Ref 2.

straints and innovations are briefly described. Inevitably, with a technology for which the initial capital cost and interest rates are of paramount importance, institutional aspects, particularly for large projects, are important and these are briefly addressed.

Hydropower as a resource

About one quarter of the hydropower potential of the world has been exploited. Such a statement, though broadly true needs some explanation. Table 1 summarizes the data on which the assertion is based, taken from the *1989 Survey of Energy Resources* by the World Energy Conference.[2] The identification of exploitable resource is not precise; one can distinguish, as Lazenby has,[3] between 'economic' and 'technical' potential. The former is the resource that can be economically developed at a cost competitive to other sources of generation and with acceptable social or environmental impact. Technically exploitable resource is that which might be developed regardless of economic or other considerations. The difference between these two is illustrated by a comparison between Table 1 and Table 2, prepared for Africa.[4] At least 225 GW and possibly 293 GW of exploitable hydroelectric resources exists in Africa. Of this less than 110 GW appears to be economically exploitable. Of necessity, the figures are approximate, but a reasonably consistent picture emerges. Europe and North America are the only regions where substantial development has already occurred. Furthermore, the only significant remaining hydropower resource and market potential in the industrialized countries is in the USA, Canada and the USSR.[5]

The evidence suggests that countries with good hydroelectric resources available at up to US¢ 8/kWh will find hydro more attractive than thermal generation when oil prices are high. When oil is cheap, or indigenous supplies of hydrocarbons are plentiful, the comparison will be more closely matched. The World Bank believes there is strong justification at the global level for substantial hydropower development in the developing world.[6]

Hydropower is capable of supplying strategically large inputs of energy. Table 3 contains a short selection of projects whose installed capacity equals or exceeds that of modern large thermal or nuclear plant. These large power plants have proved to be reliable with a better record in general than diesel or nuclear installations. Hydroplant can, however, be vulnerable to drought. Even with electricity systems

Table 2. Hydro potential in Africa.

Region	Installed hydro capacity 1990 (MW)	Economic potential (MW)	Maximum annual technical hydro potential (MW)	(GWh)
West Africa	4 158	14 645	29 975	129 080
East Africa	1 399	9 950	23 650	252 000
Central Africa	3 631	62 300	173 400	767 000
Southern Africa	5 948	22 650	66 251	297 005
Total	15 136	109 545	293 276	1 445 085

Source: Lazenby, *op cit*, Ref 3.

Table 3. Some very large hydropower installations.

Project	Installed capacity (MW)	Country
Cahora Bassa	2 074	Mozambique
Kariba	1 266	Zambia/Zimbabwe
Itaipu	12 600	Brazil/Uruguay
Tumut 3	1 500	Australia
La Grande 2	5 328	Canada
La Grande 3	2 304	Canada
La Grande 4	2 650	Canada
Dinorwig	1 800	UK

containing significant hydro with storage it is occasionally necessary during a severe drought to provide support with gas turbines or by load shedding. A good case can be made on environmental and energy resource grounds for large-scale hydropower development with large dams.[7]

Where an electrical supply system contains an appreciable proportion of hydropower three broad strategies are available to increase its resistance to drought-induced failure.[8] The first is to increase the volume of water stored where topography and environment permit; second, build additional hydropower capacity in new catchments as has been done by Norway, Brazil and Colombia; and, third, adopted more widely, include thermal generating capacity within the system.

In a mixed system of thermal and hydro, maximum benefit can be taken of the key advantages of the latter: full use of the water resource whenever it presents itself; rapid response to changes in demand; and low operation costs. Thermal plant, cheap to build but expensive to run and with much thermal intertia, can provide baseload energy. Nuclear plant fits much the same role, and tends to be used in the UK in preference even to coal fired plant.[6] Pumped storage projects used together with nuclear plant appear to provide a particularly attractive combination of low-cost baseload energy with rapidly responding hydropower. Pumped storage plant exemplifies the advantages of hydropower as a pollution free rapid response source of energy.

Kidd, in describing the use of the 1 800 MW Dinorwig Project, points out that the legal requirement in the UK is for a 1% tolerance on the declared system frequency of 50 Hz.[10] The large single generating sets on the system are 660 MW and the transmission system is switched to avoid the risk of losing more than one unit at a time. System reserve policy is based on the need to cover the unexpected loss of large machines and to cater for large-scale load swings which can amount to several hundred MW in a few minutes. Before Dinorwig was commissioned, the CEGB held about 1 000 MW of mainly partially-loaded thermal plant on spinning reserve. Once Dinorwig became available it was possible to hold the required spinning reserve on pumped storage plant at a substantial cost saving.

Pumped storage plant is also available to provide the tradional role of supplying peak power demand. It is, in addition, available to fill the trough caused by the large overnight reduction in system demand. The benefits of these operations are also large and are estimated to save about as much as the spinning reserve role.

Generation of energy from tidal power is an example of low head hydroelectric power. Studies have recently been completed on the feasibility of a tidal power project across the UK's Severn Estuary where the tidal range is one of the largest in the world.[11] Compared with conventional hydroelectric projects, particularly those with little or no storage, the operation of tidal power projects is complex. Within a single tidal cycle the water levels acting on the turbines are changing continuously depending on the tide and the operational decisions of opening sluices and running machines either as turbines or pumps. Computer based modelling is needed to analyse the interaction of the variables adequately.

The timing of the energy sent out depends on the lunar cycle, but the value of it depends on the time of day. The UK's national system must, therefore, be reinforced to take account of the large fluctuating output of the Severn Barrage: in the extreme it has to be able to support the total demand at all times whether the barrage is generating or not. Careful planning will be required to take advantage of the full output of the barrage which, at 8 640 MW represents over 15% of the maximum system demand.

Hydropower installations have a long and reliable life. Perhaps the experience over 50 years of the North of Scotland Hydroelectric Board is typical.[12] Major refurbishment of the electrical and mechanical plant has been required at most stations after 30 to 50 years operation. Generators often need new stator windings after 20 years and automatic voltage regulation equipment has to be replaced after 20 to 25 years. The pumped storage plants, operating for frequency control and spinning reserve, are subject to a greater number of mode changes than either conventional hydro, or than was envisaged when the plants were designed to provide energy transfer. However, the onerous operating regimes have been achieved only at the cost of increased maintenance of plant and tunnels. Dams have performed well and tunnels and shafts have not yet required major maintenance unlike overland aqueducts. Power stations, built of masonry, appear set for a life in excess of 100 years, given reasonable attention. Table 4 gives indicative lives of some typical components of hydroelectric projects as used in India. It is difficult to disagree with Johnson[13] that, in contrast to nuclear and thermal installations, hydropower projects can be regarded as perpetual investments with no definite limit to their lives.

Table 4. Typical useful plant lives in India.

Item	Useful life
Land	Infinity
Plant and machinery in generating stations:	
Hydroelectric	35
Steam	25
Diesel	15
Dams	100
Spillways, weirs	100
Hydropower station	35
Buildings	50
Steel pipelines	40
Underground cables	40
Overhead lines >66 kV	35
Overhead lines <66 kV	30
Transformers >100 kVA	35
Transformers <100 kVA	25
Switchgear	20
Radio system	15

RESTRAINTS TO THE DEVELOPMENT OF HYDROPOWER

Much hydroelectric potential remains to be developed in the third world. It is useful to outline some of the difficulties faced by promoters when planning, designing or constructing projects so that, where appropriate, they may be identified and reduced.

Perhaps the most significant objections to hydropower development are environmental. ICOLD has recently published a bulletin[14] that presents a realistic picture of the performance of selected schemes related to the main project purpose and to the environmental impacts of the structures and their operation. Distinguishing between preservation and conservation, ICOLD argues that mankind depends on the development of national resources and must act positively to conserve the environment from avoidable harm as a result of his activities. Experience has shown[15] that neglect of environmental aspects, linked particularly to the construction of large dams, can lead to biological degradation. It is inevitable that by altering the regime of rivers and estuaries we are changing important elements of the hydrological cycle. However, society expects to benefit from the use of energy and it is important to keep clearly in mind the environmental effects of the alternatives to hydroelectric power.

Since they encapsulate some of the most frequently quoted environmental problems, it will be helpful to summarize briefly some of the studies reported by ICOLD. They are not modern schemes and do not therefore benefit from modern engineering science. Four studies deal with projects in Arctic, temperate and tropical regions.

The Danube and Inn developments in Austria are low head, large flow projects. Although only a few power schemes were planned originally, it was soon realized that a continuous cascade was desirable both from the power generation and river morphology point of view. Extensive river training measures had been undertaken before the hydroelectric development, a function of the high population density in the valleys. Both rivers have been important for water navigation, particularly the Danube. Power station construction has taken place more or less continuously from 1919 to 1985 and some 3 500 MW of generating plant are now in place. In this period it has been possible not only to improve the local infrastructure in terms of fishing, sewage and drainage, but also to guarantee optimum ground water conditions. It was possible to rehabilitate an area that was threatened with drying out as a result of earlier bed degradation of the Danube. The ecological measures included in the power plant design have made it possible to control the irrigation to the riverine lowlands to preserve the riparian woodlands. The wet biotope thus maintained is now unique in central Europe.

Lokka and Porttipahta lakes north of the Arctic Circle in Finland provide more than 400 GWh of hydroelectric energy annually. These lakes were constructed in 1967 and 1970 in bog and forest on a tributary of the river Kemijoki. The Kemijoki river has few natural lakes and its discharge varies widely between 90 m^3/s and 4 800 m^3/s. For effective and reliable hydro generation storage was necessary. The lakes together cover over 600 km^2 and have had a significant social effect. The dominant primary production is reindeer husbandry and the loss of pasture caused a reduction in their number. As the reservoirs were planned in the early 1960s, inhabitants, particularly younger ones, started to move away, discouraged by lack of apparent planning. However, today the local economy is much improved. The service industry has expanded and the proportion of the local income structure as wages and salaries is greater than before. There is a vigorous fishing industry which has encouraged recreation and tourism.

Before construction started, extensive environmental studies were carried out into flora, fauna, forestry, agriculture, sociology and water quality. Principal among the fears was that the quality of the water downstream would deteriorate and that large areas of peat bog would float to the surface. The results of continuing studies have confirmed that the water quality deteriorated markedly initially but improved continuously thereafter. Oxygen content, for example, has returned to its original level. Floating islands of decomposing peat were observed for the first six years or so after impounding. The development of fish stocks has increased with the successful introduction of peled whitefish.

The Selingue Dam in Mali, completed in 1980, is an integral part of a multi-purpose scheme for the production of 44 MW of hydropower, irrigation, improved navigation of the Sankarani River, flood control and pisciculture. The project has been effective in providing a consistent energy contribution of over 100 GWh annually, of particular benefit to a country dependent on the import of oil.

The benefits foreseen for agriculture have not been realized despite the large volume of water made available. The problem appears to be associated with the poor condition of the irrigation structures. There has, however, been a considerable development in fishing: several thousand people make a living from this source. Over 12 000 inhabitants were displaced by the construction of the project. Some disruption was reported to the social structure as families were moved to new villages. It is claimed, however, that the social structure is gradually being restored. The constructoin of new schools has allowed an increase in the number of children in education.

The incidence of bilharzia and malaria have increased, requiring efforts to control the parasites. Except for some cases of urinary bilharzia, schistosomiasis is not a grave threat to the health of the indigenous population. There is, however, a risk that with the influx of people to the area a permanent, strong strain of schistosomiasis may become established. Malaria, once a seasonal disease, is now found all the year round. Oncocerciasis (river blindness) is rarer, probably because the larvae of the flies, that develop in turbulent water, have not survived the formation of the lake. Work is in hand to develop public health measures to control these diseases: mitigation is a practical possibility.

The Santee Cooper Project in the USA was conceived to divert the Santee River into the Cooper River, thereby producing several benefits. Significantly in the 1930s, the primary aim was to produce a peak of 12 500 jobs at a time of severe depression in South Carolina. Construction began in 1939 and the 130 MW turbines started generation in 1942, a tribute not only to the far sightedness of the government, but also to the impetus from Washington as part of the war effort. Were the project to be proposed today, concern would be expressed for the wildlife in the Santee Swamp. In 1934 the only concern was to protect the health of the human inhabitants from mosquito-borne malaria. In 1939, 1 300 malaria cases and 46 deaths were reported locally; in 1948 no case was reported. Improvements were noted in flood control and navigation. However, the environment of the 1930s gave no indication of the present burgeoning use of the project area, particularly the water ways, by present day Americans seeking recreation. In particular, the introduction of barges carrying stone through the Pinopolis Lock accidentally brought many rockfish during the spawning season. Far from resenting the new habitat, the fish prospered spectacularly, providing sport for many visitors.

A powerhouse fire stopped energy production and revealed the dependence on the power flow in the river to force the estuarial action of the river towards the sea. The implied problem of salinity in the river is not covered in the report. Siltation was, however, a problem that caused a major redesign of the project. Silt from the waters of the Santee River was deposited in the Cooper River in such large quantities that it was necessary later to redirect the Santee water back into its bed to protect the viability of the scheme.

The construction of the La Grande Riviere Complex of hydroelectric stations in the James Bay territory of Canada between 1971 and 1985 provides an illuminating example of large scale construction in virgin territory.[16] Some 10 000 MW of generating capacity was installed in an area where there was no information available on the biological and physical characteristics of the territory. Recognizing the major sociological repercussion of the project on the native population, Societe d'Energie de la Baie James (SEBJ) created an environmental department. It adopted unprecedented policies on environmental protection reflecting modern concerns with preserving a human and biophysical environment adequate for future generations.

SEBJ accepted the principle that it is the responsibility of the developer to carry out and pay for the environmental studies necessary for the project. SEBJ stipulated that:

- all environmental legislation must be complied with;
- ecological considerations must receive the same attention as technical and economic aspects;
- construction of the project must show that it is possible to develop important resources in harmony with nature.

This seems to be an appropriate basis for the implementation of hydroelectric projects everywhere. However, it has to be recognized that the cost of resettling the population and taking measures to prevent the spread of disease and other adverse measures may represent up to 10% to 20% of the total cost of a hydro project.

The La Grande Complex is in an area of weak seismic activity with no known epicentre within 100 km. The impounding of deep reservoirs can be accompanied by seismic activity and this is sometimes used as an argument against the development of hydroelectric projects. SEBJ found[17] that shortly after impounding of the reservoirs some activity was detected. At La Grande 2 for example tremors up to Richter magnitude 3.7 were recorded. Their conclusion is that the induced seismic activity has had the effect of releasing substantial amounts of stored energy in the rock below the reservoirs and that after a few years activity should decrease in frequency and intensity. The evidence suggests that in areas that are reasonably tectonically stable there is little risk of any damage occurring from reservoir-induced seismic shocks. For example, of the 25 largest reservoirs quoted in the ICOLD World Register of Dams, only four have shown induced seismicity.[18] However, in more active areas it is prudent to study the effect on the underlying rock mass of large volumes of stored water.

A restraint to hydropower development that is sometimes mentioned is that many of the best sites have already been developed. There is truth in this argument to the extent that many sites in areas of reasonably dense electrification have been developed. For example, there is little potential for further large hydro development in Switzerland or in Scotland without paying a price in environmental or social terms. A 'good' site in this connection is one at which hydropower can not only be exploited at reasonable cost, but one from which it is possible to transmit the energy economically to its point of use.[19] A reliable water run off is required together with a reasonable head. Particularly for high dams, tunnels and underground power stations, reasonably consistent and good quality rock is desirable.

The high initial cost of a hydro project, compared with a thermal alternative is a disincentive. Although front-end costs tend to weight the economic analysis in favour of thermal plant, the economic analysis should perhaps be regarded as a yard stick. Future costs, market development and hydrology are unknown and discounting, as is conventional, provides safety against the growing uncertainty with time. However, the paradox exists with conventional analysis that a 30-year old scheme may be in excellent condition and earning valuable income for the foreseeable future; but this very income would scarcely have influenced the initial economic decisions. Analytical methods are available in which the initial heavy capital cost is annuitized over the study cycle and appears as an annual cost over the redemption period of the scheme. Both analyses are critically dependent on the discount rate used. An advantage of the second method is that perhaps the continuing statisfactory performance of the project is more visible.

Fluctuation in the oil price is another factor to retard investment in hydroelectric projects. While the oil price rises of the 1970s were partly responsible for the expansion of hydro capacity in the 1980s, the decline in oil price since 1986 may have had the reverse effect. There is the danger that a short-term signal may be misinterpreted and lead to errors in long-term planning. It is worth restating that hydro projects have a long gestation period and a project life that is considerably longer than any alternative. Johnson[20] suggests that overall, more than 100 years is appropriate. In this time period, the likelihood is that oil will become scarcer and more expensive.[21]

TECHNICAL INNOVATIONS

Occasionally an innovatiuon has an historical effect on those that follow. The internal combustion engine for example, or the wheel. With today's perspective, the art of the development of hydropower is progressing steadily on a wide front. Engineers, not infrequently acting alone or in small teams, develop an idea that benefits all. The concrete faced rock fill dam is an example of the process. Such a structure benefits from the relatively low cost of a rock embankment, enhanced by there being no internal waterproof membrane to restrict the speed of construction. Watertightness is assured by a concrete membrance over the upstream face. The Hydroelectric Commission of Tasmania have over the last 20 years or so introduced and developed the design to the extent that it is now a widely used technique, particularly where the foundation rock is not of the highest quality. More recently, additional cost savings have been introduced by the same engineering team in developing a flexible concrete spillway that is installed directly on top of the rock fill dam. The saving in cost of a separate spillway is appreciable.

Until 1960 the proportion of dams being constructed conventionally of concrete was increasing: from 1933–37 the percentage increased from 33% to 37%. Since 1960 this has decreased, perhaps because of the relatively low cost of embankment dams benefiting from improved efficiency in transporting and compacting earthfill and rockfill. The conventional method of constructing concrete gravity dams relies on casting a series of monoliths separated by contraction joints. The method is effective in preventing temperature cracks, but the equipment for cooling and grouting makes the method less economical than embankment dam construction. It is not usually possible to use large-scale machinery on a concrete dam because of the small construction area. On the other hand, embankment dams lack resistance of their materials to overtopping by floods. Roller compacted concrete dams share many of the advantages of both dam types.[22] Roller compacted concrete (RCC) is prepared and placed differently from conventional concrete and construction is achieved at a substantially reduced cost and, more importantly a shortened construction period. Roller Compacted Concrete is placed in a similar way to earth or rockfill, in long and continuous layers and is consolidated by heavy vibrating rollers. The technique has been available since about 1975 and today it is being used in many countries for gravity dams over 100m high. Its use in the construction of arch dams will no doubt extend the benefits further.

Much attention is being given currently to the rehabilitation of aging hydroelectric facilities.[23] There is a considerable stock of projects that are 50 years old or more, dating for example from the activities of the British in India before independence, in ex-colonial Africa and in the USA. Many of these installations were well designed and built, and appropriately sized at the time. They were intended to operate at a high load factor to provide a reliable supply to a relatively small area. With economic development and the construction of high voltage transmission lines it has become worthwhile to reconsider their role. Typically, more plant can be economically added so that operation is at a lower load factor, supplying more energy and particularly peaking power. Thus the system benefits from a useful incremental input at no environmental cost and a modest financial cost.

ICOLD has established a committee to study the question of the aging of the civil engineering components of hydro projects. As the causes of aging become better understood, not only will new projects be designed for a longer life, but also older installations will be more effectively rehabilitated. The situation is complicated; it is not unusual to find that there is a cultural influence at work in the design and construction of hydroelectric projects. Some very old installations are in better condition and have a longer life expectancy than more modern plants.

Among the specific reasons for premature aging can be counted the chemical instability of some concrete mixes particularly when specific types of silica-rich aggregate have been used in conjunction with highly alkaline cement. Poor maintenance is another factor, raising the delicate issue of the quality of training of the local staff.

Improvements to designs that can reduce the cost of important elements by a few percent are welcome to promoters of schemes. An example of such an advance can be found in the design of pressure pipelines, often known as penstocks. Traditional designs use expansion joints to allow the pipes to react to changes in temperature and pressure. The essential concomitant is that the pipe must be secured with heavy anchor blocks made of concrete. More modern pipelines can now be designed without expansion joints: the thermal and other stresses are carried within the pipeshell itself. Such a development relies a little on improved calculation methods, but more on greater efficiency in producing high quality, defect-free welds in the field. The legacy of the failure of the Liberty Ships and the requirements of the oil industry have together conspired to produce a better understanding of the metallurgy required to overcome brittle behaviour.

Within a generation, knowledge of the behaviour of geotechnical materials, rock and soil, has increased dramatically. Some of the benefits are becoming available to those promoting hydroelectric power. At the recent 17th ICOLD Congress one of the four questions to be addressed is that of poor foundations. Engineers are increasingly confident of their ability to strengthen foundations by injections designed to stiffen weak materials. Elements are being considered for installation within liquefiable soils to control their behaviour during earthquakes. Attention is being given to the use of low quality fill materials: the cost–benefit of being able to use effectively all the material excavated for other purposes can easily be imagined Much research has gone into the use of manmade materials, geotextiles, to strengthen soils, and provide a wide range of tools to provide more effective geotechnical structures at a lower price.

Recent developments in tunnelling methods have been spectacularly demonstrated by the achievements in connection with the Channel Tunnel. The speed, reliability and size of available machines together with their ability to tunnel through a wide range of material from hard, competent rock to sand and gravels, all act powerfully to increase the range of sites at which a hydropower project can economically be constructed. The development of shaft-making equipment is perhaps even more spectacular. By using a technique such as raise boring, a shaft some 300 m deep and 7 m in diameter can be excavated in a matter of a few weeks.

Although finite element analysis, a mathematical modelling method, has been known and used for a generation, it is relatively recently that software and computers have been developed to allow the method to be used routinely in design offices. Its present use to optimize the design of highly stressed elements such as generator and turbine supports or arch dams, allow significantly improved understanding of specific structural behaviour in a very short time. Alternative designs are easily evaluated with the prospect of lower cost structures. Attention is being focused currently by ICOLD on advanced computational techniques, particularly in taking advantage of the three dimensionality of dams in narrow valleys.

INSTITUTIONAL ASPECTS

The financing of large hydroelectric projects is a key issue. This is particularly so when the river to be developed is shared by more than one country. The problem is exacerbated when the differing cultures of the countries involved require responses that are so at variance that effective communication breaks down. In severe situations a scheme can be abandoned with heavy losses.

An example of this tragic situation is the Gabcikovo–Nagymaros Project on the Danube shared by Hungary and Czechoslovakia. The scheme, as described by Lokvenc and Szanto[24] was designed to provide flood protection, navigation improvements and hydroelectric power on the stretch of river between Bratislava and Budapest. Difficulties have traditionally been encountered by shoaling at the point near Gonyu where the river slope flattens. Much of the sediment carried in the steep reach upstream is deposited where the gradient flattens, requiring much attention to maintain navigation. A 700 MW power plant was planned upstream of the change of gradient at Gabcikovo, and downstream a 158 MW plant at Nagymaros. The annual output was to be about 3 675 GWh.

Work started on preliminary works in 1978 shortly after the bilateral agreement was signed between Czechoslovakia and Hungary in 1977.[25] In 1986 it was reported that work was under way on the Czechoslovak side which includes the Gabcikovo plant. In the same year preparatory works were reported on the Hungarian side. Even in the early stages some concern can be detected over the cost of the project, its economic justification and its environmental impact. Tensions grew between Hungary and Czechoslovakia as the true cost of the project became apparent. Austria agreed in 1987 to finance the Nagymaros part of the scheme through an agreement with Hungary under which Austrian firms would provide some US$400 million for the construction of the power plant. Austria was to be repaid in energy at 1 200 GWh/year for 20 years, allowing a reduction in the use of thermal plant relying on imported fuel. Perhaps significantly the programme was reported as having been substantially delayed again. Meanwhile Czechoslovakia was proceeding enthusiastically with its work on the upstream Gabcikovo works.

In addition to the obvious difficulties caused by the cost of the project, wide criticism now began to be heard from Hungary and Austria on environmental grounds. Protests were heard at the loss of 100 km^2 of ecologically valuable wetland. Protestors occupied the Austrian Embassy in Budapest. Despite reports of good construction progress in 1988, the Hungarian government suspended work on the project in 1989. This decision followed political pressure on the government of Austria and Hungary by those concerned at the cost and environmental impact of the scheme. Both the Czechoslovakian Government and Austrian companies and bankers were less than happy with the decision. The Czechs were upset because the Gabcikovo power scheme, that was by now nearly complete, would be much less productive without the downstream element.

The Austrian companies and bankers were also dismayed at the potential commercial loss the decision represented. The commercial problems were complex, not only because the Austrian companies had employed Hungarian sub-contractors, but also commercial agreements between Soviet bloc countries apparently did not accept the principle of unrealized profit. The Czech government calculated that it was due US$3.5 billion and the Austrians US$1.3 billion. The problem appears to be from whom to claim compensation. The political repercussions of the tragedy are not yet complete. It is reported[26] that the Hungarian Ministry of Water Management was closed down following the public outcry over the scheme which appears not to have been subjected to rigorous economic or environmental examination.

An important financial instrument devised recently to facilitate delivery of power plant equipment to developing countries is build-own-operate-transfer (BOOT) and variations. The idea is that a power plant is built by a consortium of usually foreign-led suppliers, who earn income from the project through revenues from the sale of electricity into the client country's national grid. It is intended as a cost-effective way to curb drains on developing countries' national treasuries.

BOOT projects are usually long term, often more than 10 years. Hopewell Holdings Hong Kong's 700 MW Shajiao B power station in China is an example, as is the proposed 4 x 323 MW oil-fired power station proposed for Hab River in Pakistan. The World Bank[27] has recently issued working papers of a BOOT seminar held in 1990. Some 14 BOOT projects are reported to have been under way during 1990. Most of these involve oil and gas pipelines, transport or thermal power. Hydropower projects are less attractive subjects for BOOT contracts for two principal reasons: the high initial cost, and the long period of time that has to elapse before these costs are recovered. Both spell risk. The World Bank's seminar on BOOT describes many of the tensions between private and public investment in power projects in general: these are at least as valid in hydropower projects and serve to illustrate some of the institutional aspects of developing them.

While personal savings rates in developing countries are relatively high when compared with the developed world, there are inadequate opportunities to put the available funds to use. Developing countries sometimes insist on maintaining public ownership and control of investment by utilities. They have operated the institutions in such a way that they are unattractive to private capital. What resident of a developing country would invest his own money in the country's public utilities when these are likely to be effectively bankrupt? Issuing shares and encouraging dealing would be a valid way to mobilize indigenous capital through boardroom control.

Share issues would also be an important factor in encouraging BOOT contracts. A major long-term foreign investor is unlikely to be interested in a project that will be transferred back to the state on a knock down basis. A better solution might be to encourage an initial small investment by the local market, which could then be increased appropriately by the transfer of shares.

Early BOOT projects in the USA were small power stations of 5 MW to 10 MW and financial risk was small. Large projects, say, 1 000 MW or so require the involvement of so many banks that assembling the team becomes expensive. If the negotiations take too long fundamental assumptions become invalid; governments themselves can change unpredictably. The local legal and regulatory infrastructure may need to be strengthened by complex contractual arrangements.

There are three elements to a tariff agreement: a capacity charge, an energy charge and a variable element that rewards availability or reliability. If the host government has no mechanism for establishing a market price for energy it may be appropriate to offer capacity only. The private developer will be keen to establish cost indices to ensure that the cost elements of the tariff are covered. The host government may well favour a tariff structure that requires the project to achieve a target output to earn a return for investors.

Some have misgivings about the host government failing to follow the rules. Some governments practice 'creeping nationalization' rather than outright expropriation. They may, for example, fail to raise prices, create difficulties in the movement of foreign currency, insist on local labour that may not have appropriate skills.

The governments of developed countries have frequently used hydropower development to create employment, not only on the project itself but through a Keynsian multiplier affecting other industries attracted by the energy. Hoover Dam in the USA is an example of this as is the early work of the US Bureau of Reclamation generally. The development of the hydropower potential[28] of Scotland after World War Two appears to have been motivated to some extent by the benefits gained by local employment. This would have been particularly important at a time of net migration of population from the Highlands, and the potential unemployment caused by returning servicemen. Similar arguments were, no doubt, raised when the Snowy Mountains Scheme of Australia was proposed in the 1940s.

The development of Scottish Hydro provides an interesting study in the merits of private and public investment. The first significant hydro scheme there was commissioned in 1896 at Foyers (4 MW) on Loch Ness[29] for the reduction process of aluminium. Kinlochleven (23 MW) and Lochaber (80 MW) followed in 1909 and 1928. During the early 1930s high voltage transmission lines encouraged private companies to build the 107 MW Galloway Scheme on the Kirkcudbright Dee and the 80 MW Grampian Scheme on the Tummel. The formation of the North of Scotland Hydroelectric Board (NSHEB) after the war brought about the construction of 28 schemes with a capacity of 965 MW. These were followed in the late 1960s and early 1970s by the two pumped storage schemes Cruachan (400 MW) and Foyers (300 MW). At this time, the NSHEB has just been sold as part of the UK's privatization programme.

When the hydro schemes were promoted after the war both coal and money were cheap. Annual interest rates were 2.5% to 4%. Coal was in short supply. However, despite this, difficulties were experienced, from landowners among others, by those who did not accept that hydropower was as secure a source of electricity as thermal generation. Despite this, and the increases in interest rates over the intervening period, Johnson[30] asserts that the cost of energy generated by hydro in Scotland is very considerably below that of other forms of generation. Attempts by the NSHEB to promote two schemes since 1965 have failed on the grounds that fossil fuelled plant could be built more economically. The NSHEB has more recently investigated small run-of-river plants which can produce power at less than the system marginal fuel cost, the cost of fuel in a modern coal fired station.

The experience of the Hydroelectric Commission (HEC) of Tasmania is not dissimilar:[31] early private development, stimulated by mineral mining and processing was sold to the state. The HEC was formed in 1929 and in 1969 produced 3.6 TWh of energy at a load factor approaching 70% and at 0.76 c/kWh the lowest price in Australia. Although particularly favoured by geography, Tasmania has in the past considered the introduction of thermal plant notwithstanding its inability to produce energy cheaper than hydro. The key issue was the scarcity of sufficient capital to build the hydro plant. The HEC, a state instrumentality responsible to parliament, has been able to coordinate the development of hydropower within the state to a remarkable degree. In 1969 for example, Tasmania consumed nearly 19% of the Australian total generation of electric power despite having less than 5% of the Australian population. In recent years the bitter battles over the development of the hydroelectric resources of the wilderness areas to the west of the island have, perhaps, been the more civilized through being fought with a highly technically competent professional organization responsible to parliament.

The example of the HEC, the NSHEB and the Snowy Mountains Hydro Electric Authority, show the value of state enterprise in constructing hydropower projects. At a current construction cost in the region of £1 000 per installed kW, these three major developments would have cost billions of pounds. The HEC, for example, in 1969 was carrying over A$300 million in debt, almost all of it to the state Treasury. One can distinguish perhaps between the conception and construction of large hydropower projects on the one hand, and their subsequent operation on the other. In the operation phase there is less to be gained from state support, and it could be argued that a private company, sensitive to the demands of shareholders and the market, would provide the least-cost operation of the facility once built.

CONCLUDING REMARKS

Even a superficial treatment of the subject is enough to confirm that hydropower, despite its being a well established technology, still has a major role to play in meeting our energy needs in the future. There is much potential still to be exploited, particularly in the developing world. Economies of scale will often favour large projects, possibly with high dams. Modern techniques will be needed to address the environmental questions posed by these large structures. Technical advances will no doubt continue to reduce the cost and construction time of hydropower projects. To take advantage of these, improvements would be welcome in the effective implementation of projects, particularly those involving more than one country or smaller, poorer states. It would be useful too if economists could suggest an analytical method that takes appropriate advantage of the long life of hydropower projects and doesn't penalize them unnecessarily for their high initial cost. The future looks bright for hydropower; a relatively benign means of generating power without depleting our precious fossil resources.

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Chapter 7

Tidal Energy

Clive Baker

The tides represent a large and benign source of renewable energy which can be converted to electricity using well-proven technology. The origin and nature of tidal power is summarized first. The main components of a tidal barrage, and the method of operation are described. The parts of the world where the tidal range and coastline are suitable for tidal barrages of substantial size and capable of generating electricity at an acceptable cost are relatively small in number but the UK has a substantial share.

Keywords: Tidal power; Electricity generation; Renewable energy

The rise and fall of the tides represents a predictable and truly renewable source of energy which has been exploited at very small scale for milling since the twelfth century. The tides are generated by the rotation of the earth within the gravitational fields of the sun and moon. Although the gravity force exerted on the earth by the sun is about 177 times stronger than that of the moon, the moon is the dominant force as regards tides by a factor of about 2. This apparent paradox arises because it is the difference in the gravitational field on opposite sides of the earth which distorts the seas and the ratio of the earth's diameter to the distance of the moon is much greater than this ratio for the sun.

The theoretical mean tidal range in the open sea, ignoring the land masses, would be about 530 mm and the times of high water are linked to the passage of the moon and thus occur about every 12 hours and 25 minutes. The process by which this range is increased at some coasts and not others is complex, involving the steepening of the tidal wave as it enters shallow water, and an element of resonance wherever the length of an estuary or bay is close to a quarter of the length of the tidal wave. The Severn estuary in the UK and the Bay of Fundy, where the tidal range can exceed 14 metres, are famous examples. A further factor is the Coriolis force which, north of the equator, causes currents travelling north to curve to the east and vice versa. This results, for example, in tides in Liverpool Bay being much larger than on the opposite side of the Irish Sea. For tidal power to have any real prospect of being economic, a mean tidal range of at least five metres is necessary, partly because the energy available is proportional to the square of the tidal range.

OPERATION

Recent studies, particularly of the feasibility of the Severn barrage,[1] have shown that in most circumstances the best method of operating a tidal barrage is to trap the incoming tide at high water behind a barrage and release the water, through horizontal-axis turbines, from the basin to the sea during the second part of the ebb tide and the first part of the next flood (Figure 1). This method can be augmented by using the turbines in reverse as pumps at high water in order to increase the water stored in the basin.

If the local grid system is weak, then operation in both directions may be preferable but this results in less energy per turbine and high water levels within the basin will be lower than at present. This method, combined with pumping, was adopted for the 240 MW barrage on La Rance, near St Malo,[2] which has been operating for over 20 years but which is now operating largely as an ebb generation scheme with pumping at high water.

Another option is flood generation, where the basin is emptied at low tide and the turbines discharge into the basin before and after high water. This method could apply where the barrage has a land drainage role and water levels in the basin must be kept low.

COMPONENTS OF A BARRAGE

The heart of a tidal barrage is its turbines. A variety of turbines could be used but the type generally favoured is the horizontal-axis Kaplan (propeller) turbine. This has four blades which are usually adjustable-pitch. Upstream is a 'distributor' com-

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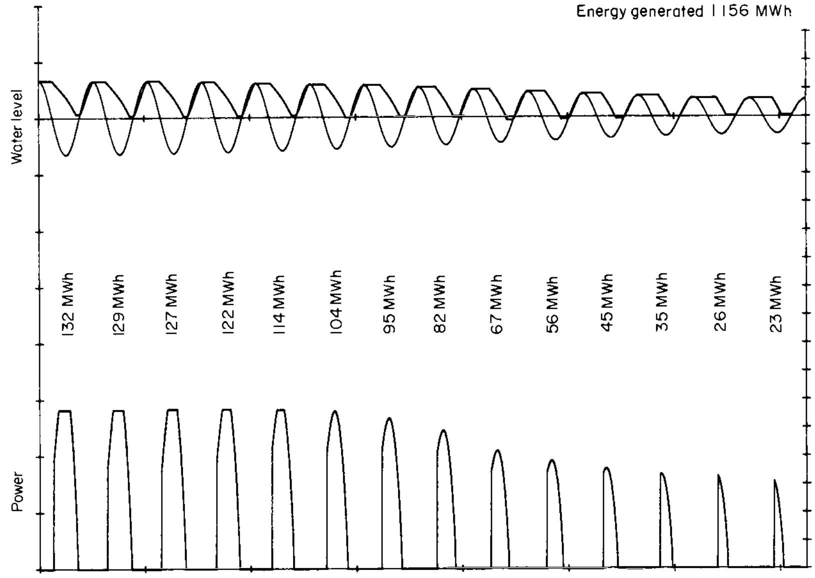

Figure 1. Near optimum ebb generation over 14 tide spring–neap cycle.

prising up to 20 guide vanes, again usually adjustable for angle, which impart an intial swirl to the water so that the runner blades can 'fly' through the water in the same manner as an aerofoil. Runner diameter may exceed seven metres. The generator can be direct driven or driven through a step-up gearbox, or mounted on the rim of the runner, the 'Straflo' turbine. If of one of the first two types, it can be either enclosed in a steel bulb within the water passage, the 'bulb' turbine, or in an open-topped pit. Turbines for tidal power are relatively slow-turning, usually in the range 50 to 100 rpm.

To refill the basin after the end of the generating period requires a number of gated openings or sluices. These also play a key role during the later stages of construction as they provide a passageway for the tides while the rest of the barrage is being built. There are several types of gate which are suitable, including radial gates and vertical-lift wheeled gates.

Both the turbines and the sluices may be housed in concrete structures which can be built in suitable workyards on shore and floated into position. These are called caissons and, for the Severn barrage, scores of such caissons would be needed, each weighing more than 100 000 tonnes.

The remaining parts of a tidal power barrage will include embankments joining the deep water structures to each shore, and ship locks where there is commercial navigation to be accommodated. The minimizing of any delays to shipping is one of the key aspects of tidal power, as some of the prime estuaries such as the Severn and the Mersey are also busy shipping routes. Thus two locks would be needed, partly to guard against the risk of one being closed by accident and isolating the ports behind the barrage. Such locks would have to be operational before the rest of the barrage is completed and thus lie firmly on the critical path. In addition, they are costly and 'non-productive' elements of a barrage.

The Rance barrage was built in-situ behind large and expensive temporary cofferdams. Several small schemes have been built in China[3] by constructing the power house and sluices on dry land beside the estuary and then excavating a channel to the estuary while closing the estuary with a dam. Only one tidal power scheme has been floated into position, namely a pilot 240 kW single caisson in the Gulf of Mezen in the White Sea. However, although the direct experience of large tidal power schemes is limited, much relevant experience has been gained on other projects with each of the main components. For example, hundreds of low-head Kaplan turbines have been built for run-of-river projects, while float-in concrete caissons have been used for under-sea road crossings and the largest single object moved by man is a one million tonne concrete caisson for the North Sea oil fields. Given careful design, choice of materials and quality of construction, concrete is very durable, even in salt water. Thus a barrage should have a long working life, certainly more than 60 years.

THE RESOURCE

So far, apart from La Rance, which has been working sucessfully for over 20 years, the Gulf of Mezen

Table 1. Potential tidal power sites.

Site	Area (km^2)	Max depth (m)	Length (m)	Mean range (m)	Turbines (No × dia)	Annual energy (TWh)	Unit cost (p/kWh) (1983 prices)
Argentina and Chile							
Golfo San Jose	788	25	7 000	5.78	270 × 7.5	10.9	2.1
San Julian	77	13	810	5.66	40 × 6	1.04	1.8
Rio Santa Cruz	215	32	2 070	7.48	60 × 9	5.05	2.3
Rio Coig	46	12	1 800	7.86	30 × 6	0.61	1.9
Rio Gallegos	140	12	3 400	7.46	85 × 6	3.27	1.6
Bahia San Sebastian	580	30	19 300	6.5	145 × 9	10	3.8
Australia							
Secure Bay	140	50	1 300	7	37 × 9	2.9	3.6
Walcott Inlet	260	75	2 500	7	70 × 9	5.4	5.1
Canada							
Bay of Fundy (site B9)	282	42	8 000	11.7	106 × 7.5	11.7	2.2
southeast China							
Damao shan (3.7)	200	24	3 550	4.8	100 × 6	2.05	3.7
Dongan Dao	210	21	3 900	5.1	100 × 6	2.26	3.2
Santu Ao	680	35	3 000	4.8	150 × 9	3.7	2.8
India							
Gulf of Cambay	1 055	22	25 000	6.1	570 × 6	16.4	2.5
Gulf of Kachchh	50?	18	2 000	4.8	24 × 6	0.48	5
South Korea							
Garolim Bay	100	28	1 850	4.8	24 × 8	0.893	4.5
Gulf of Asam	130	24	2 350	6.06	72 × 6	2.05	3.1
USSR (Sea of Okoskh)							
Zaliv Turgurskiy	1 400	30	26 000	4.74	200 × 9	12	4

pilot scheme and the small Chinese schemes already mentioned, the only other operating scheme is a 7.6 m diameter, 20 MW single Straflo turbine at Annapolis Royal, a small estuary off the east coast of the Bay of Fundy in Nova Scotia.[4] This was commissioned in 1984 as a prototype for both tidal power and run-of river schemes, and is proving highly reliable.[5]

There is a limited number of locations where the mean tidal range is five metres or more and the coastline is suitably indented so that a barrage could enclose a basin or estuary which has a large area in proportion. As already mentioned, the UK has more than its share on the west coast, while one of the reasons that France has not proceeded with more tidal power after the success with the La Rance barrage is that there are no more sites nearly as favourable.

Possible sites around the world have been evaluated in terms of their energy resource and likely unit cost of energy (at 1986 prices and 5% real rate of interest) using a parametric method developed by the author.[6] These are listed in Table 1. Many of these sites are remote from centres of demand and therefore, although representing very substantial resources at reasonable unit cost, there is little chance of their development in the foreseeable future. The main interest at present lies in the Bay of Fundy,[7] Garolim Bay[8] on the west coast of south Korea, the Gulf of Khachchh on the west coast of India,[9] a 36 MW scheme on an existing flood-defence barrage near Sao Luis[10] on the north coast of Brazil which has been announced as proceeding, and in the UK.

PROSPECTS IN THE UK

In the UK, feasibility studies of tidal power schemes are in progress or have recently been completed of the following estuaries: Severn; Mersey; Humber; Conwy; Wyre; and Loughor. Of these, the Severn represents a major national resource but, at about twice the capital cost of the Channel Tunnel, would

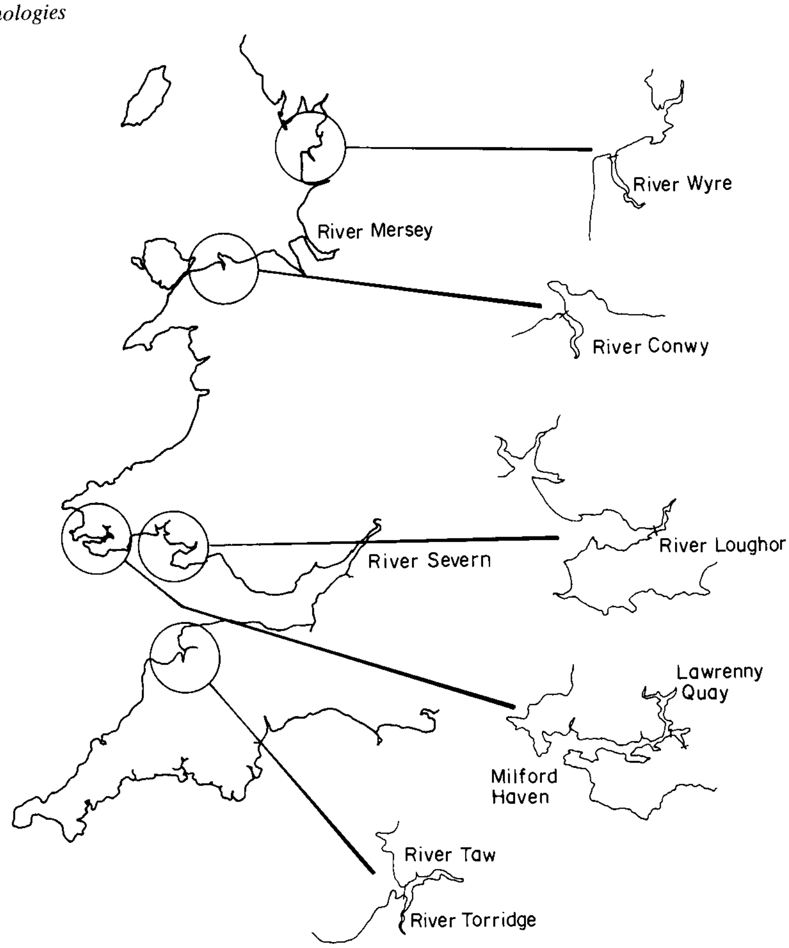

Figure 2. Locations in some small sites in the UK worthy of further study.

be a huge undertaking. It has been studied in great detail over the last 12 years, first on behalf of the Severn Barrage Committee and lately by the Severn Tidal Power Group, a consortium of major civil engineering contractors and turbine/generator manufacturers.[11]

A central issue is the discount rate to be used when comparing investment in the Severn barrage with other forms of electricity generator.[12] The Severn Barrage Committee report concluded that, at 5% real rate of interest, electricity from the Severn barrage would be cheaper than from coal but more expensive than from nuclear stations. Since then, the application of higher discount rates (and dismantling costs) has seen nuclear energy fall by the wayside and the cost of the electricity from the Severn barrage become unattractive. Whether this is a correct evaluation of relative worth is open to question; hydroelectric projects are seen as excellent investments only with the benefit of hindsight.

The Mersey[13] would be about 10% of the size of the Severn barrage and is at an advanced stage of study by the Mersey Barrage Company with the support of the Department of Energy and a number of companies with local interests. The Humber has been the subject of a pre-feasibility study carried out as a privately funded project for the Humber Barrage Group.[14] The report has not yet been made public. A site between Hull and Immingham is recommended which could also have a multipurpose role.

The Conwy, Loughor and Wyre are small schemes (See Figure 2), with capacities of about 35, 8 and 45 MW respectively. The first two have already been studied in some detail and the last is currently the subject of a feasibility study being carried out by Trafalgar House Technology and Binnie & Partners on behalf of the Department of Energy and Lancashire County Council.

The Loughor barrage near Llanelli in south Wales could form the basis of waterside development but it proved to be too small and too shallow for its unit cost of electricity to be attractive.[15] The Conwy estuary in north Wales is a sensitive area suffering temporarily from the construction of the A55 submerged tube crossing. A tidal barrage here would be nearer to being economic and would make water-based recreation much more acessible.[16] It would be located at the mouth of the estuary, well clear of the famous castle and medieval town of Conway. Thus local tourism should benefit greatly (the Thames barrier attracts about 200 000 visitors a year and La Rance barrage a greater number). Unfortunately for any promoters of a barrage, these and other benefits, such as protection of the estuary against very high tides, accrue to the region rather than to the promoter of the barrage. This points to some public sector participation being required if tidal power in the UK is to reach construction.

A tidal power barrage near the mouth of the Wyre estuary, behind Blackpool, could provide a road crossing, a 7 km^2 semi-tidal lake for sailing and boating, and a flood defence capability. This would allow the shores of the estuary to be developed as the planners saw fit. The electricity cost is expected to be close to the minimum for tidal power in the UK.

The Conwy and Wyre barrages would be built using float-in 'caissons', the method proposed for the Severn barrage. This method offers the minimum local disruption. Although all aspects of caisson construction for tidal barrages have been studied in much detail, with appropriate computer models, the building of a small barrage such as the Wyre would provide useful practical experience at prototype scale and thus improve confidence for the larger schemes.

ENVIRONMENTAL ASPECTS

Flood protection and opportunities for water-based recreation have already been mentioned. There are many other aspects, most of which have been the subject of much study and appropriate field work, particularly in connection with the Severn barrage. A few key aspects only can be covered in this paper. The most important are probably water quality and sediment movements, because these govern to a large extent the ecology of the estuary.[17] One unavoidable change in water quality behind a barrage is that, in the upper estuary away from the immediate effects of the barrage, salinity will reduce as a result of the reduction in the volume of seawater entering the estuary each tide. Thus freshwater species will extend their domain seawards, while the brackish water zone, which tends to be relatively impoverished, will move downstream.

In the basin behind and clear of a barrage, tidal current velocities will be reduced, particularly during the ebb. This will have a major effect of the power of the currents to erode and transport sediments. The effect will be a general 'freezing' of sediments which are normally mobile, especially during spring tides. This will in turn reduce the turbidity of the water and provide a more stable regime for organisms which live in muddy deposits. One result could be an increase in invertebrate populations which would benefit wading birds.

Because a tidal barrage would lie across the path of mobile sediments, there is a risk that the sediments moving upstream with the flood tide would be deposited inside the basin at high water and would not be re-suspended during the ebb because the strength of the currents would be reduced markedly. The importance of this will depend on the availability of fresh supplies of fine sediment seaward of the barrage. This aspect has been studied in great detail with the aid of computer models of water movement. For the Severn barrage, the risk is associated with the possible loss into the basin of the large deposits of sediments in Bridgwater Bay, the southern part of which is an important area for wading birds and Shelduck. For the smaller barrages discussed earlier, progressive siltation of the basin will take place slowly over decades, offset by scouring during large river floods.

CONCLUSIONS

Tidal power is a benign, relatively concentrated and highly predictable source of renewable energy. To exploit it will not require new technology to be developed; instead, the concepts on which all the main components are based have been used extensively in similar conditions for other purposes such as offshore oil fields, marine defences and run-of-river hydro projects. Thus the capital and maintenance costs can be predicted with confidence.

The environmental effects of tidal power schemes centre on the changes that will be unavoidably caused to the salinity and sediment regimes in the enclosed basins, because these largely govern the primary productivity of the water. The fact that changes must take place gives rise to concern, but the changes are not all for the worse.

Tidal barrages have a multi-purpose function, including flood protection. Increases in low-water levels and a general reduction in currents and turbidity will make the enclosed basins more attractive for water-based recreation. The resulting economic benefit to the area cannot easily accrue to the promoter; this points to some public sector participation in the development of tidal power.

The locations where tidal power could be developed economically are relatively few, because a mean tidal range of five metres or more is needed for the cost of electricity to be competitive with traditional thermal plant. The UK has its fair share of potential sites[18], ranging from 30 MW to 8 000 MW. However, the economics of tidal power are critically dependent of the choice of discount rate, particularly because a well-engineered project will have a working life of at least 60 years. Thus, a high discount rate, as would be applied by a private developer, does not give credit to this long life and results in an unattractive unit cost of electricity. In practice, and with the benefit of hindsight, hydropower projects become very attractive a few years after they are built.

This article is based largely on work carried out for the UK Department of Energy and permission to publish is acknowledged.

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Chapter 8

Geothermal Energy

– electricity generation and environmental impact

Ronald DiPippo

Geothermal energy is widely used as a reliable source of electricity generation. In 21 countries geothermal plants are in operation and have a combined installed capacity of over 6 000 MW. Technology now permits the utilization of a broad range of resources, from moderate-temperature to hypersaline brines, as well as natural steam with high levels of non-condensable gases. This paper describes geothermal energy conversion systems and the potential environmental impacts associated with geothermal plants. In comparison with alternatives, geothermal plants are among the most environmentally benign. Emissions abatement, water and land-use, and other aspects are discussed, along with the costs for environmental controls.

Keywords: Geothermal energy; Environmental impact; Electric power

Geothermal energy is being used to generate electricity in 21 countries on all non-polar continents. At the end of 1990, the total worldwide installed capacity stood at 6 017 MW distriobuted over 330 individual turbine-generator units. This is roughly equivalent to six typical nuclear power plants or a dozen coal-fired plants, and to the power needs of about six million people living in the USA. The USA in fact accounts for about 47% of the total installed geothermal capacity. Table 1 shows the worldwide status of geothermal plants.[1]

ENERGY CONVERSION SYSTEMS

The most appropriate type of energy conversion system for a geothermal site is determined by the nature of the particular resource, ie, whether the reservoir fluid is vapour, liquid, or a two-phase mixture, its temperature and pressure, salinity, acidity, and the amount and type of non-condensable gases.

In the following sections we give a brief introduction to some of the commonly-used geothermal power systems, focusing on their basic operating principles. Later we will identify the potential environmental impacts and compare them with other types of power plants. For the most serious impacts, we will describe mitigation techniques and their costs. We also discuss the economic and institutional factors relating to geothermal energy and assess the future prospects for this energy source.

Direct steam plants

Direct steam plants are used with vapour-dominated resources.[2] Steam from production wells is gathered and transmitted via pipelines directly to a steam turbine. In principle, this is all that is required, but practical power plants require several other items. These include: small, in-line centrifugal cyclone separators near the wellheads to remove particulate matter such as rock dust; drain pots along the steam pipes to remove condensate that forms during transmission; and a final moisture removal separator just before the steam enters the powerhouse.

The turbine backpressure is chosen in accordance with the amount of non-condensable gas in the steam and environmental restrictions at the site. The turbine may be either condensing or non-condensing. While at most geothermal sites in the USA continuous direct discharge of geothermal steam from a power plant to the atmosphere is prohibited, this type of operation is not ruled out in many countries. Non-condensing units are very simple, relatively inexpensive, and can be constructed and installed rapidly (in a few months), but operate at low efficiency and may have detrimental effects on the environment owing to the direct discharge of untreated geosteam into the atmosphere. In most

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Table 1. Geothermal power plants worldwide – 1990.

Country	Plant types[a]	No units[b]	Total (MW)
USA	DS, 1F, 2F, B, H	168	2 852.99
Philippines	1F	23	894.0
Mexico	DS, 1F, 2F	24	720.0
Italy	DS, 1F	38	546.0
New Zealand	1F, 2F, B	16	286.0
Japan	DS, 1F, 2F	11	270.3
Indonesia	DS, 1F	5	142.25
El Salvador	1F, 2F	3	95.0
Nicaragua	1F	2	70.0
Kenya	1F	3	45.0
Iceland	1F, 2F, B	8	42.9
Turkey	1F	1	20.6
China	1F, 2F, B	15	14.586
USSR	1F	3	11.0
France (Guadeloupe)	2F	1	4.2
Portugal (Azores)	1F	1	3.0
Romania	B	3	1.5
Argentina	B	1	0.6
Thailand	B	1	0.3
Zambia	B	2	0.2
Australia	B	1	0.02
21 countries	DS, 1F, 2F, B, H	330	6 017.446

Notes: [a] DS = dry steam; 1F = single flash; 2F = double flash; B = binary; H = hybrid; [b] a 'unit' is defined as a turbine-generator set.

direct-steam plants having capacities greater than 5 MW, plants are fitted with condensers and gas extraction systems. The condensed steam is cooled in conventional cooling towers and re-circulated as cooling water for the condenser. External cooling water is not required. In fact, excess cooling tower water is available to assist reservoir recharge. Roughly 15% of the mass extracted may be returned to the reservoir via re-injection.

Direct steam plants are capable of very high thermodynamic conversion efficiencies, based on the Second Law.[3] Such plants are able to convert 50–70% of the available work (or exergy) of the geosteam to electricity.

Flash steam plants

When the fluid in the geothermal reservoir is a pressurized hot liquid or a mixture of liquid and vapour, a self-flowing well will produce a two-phase mixture at the wellhead. Considering the potential damage to the turbine if the total flow were admitted to it, the steam must first be separated from the liquid. The simplest technique involves the use of centrifugal cyclone separators.[4] The total flow from the well is directed tangentially and horizontally into a vertical cyclindrical vessel. Typically a vertical central stand-pipe conducts steam out through the bottom of the vessel, through a ball check valve, and into a pipe for transmission to the powerhouse. The liquid is drained from the separator under gravity and may be either flashed to atmospheric conditions before disposal or conveyed under pressure directly to re-injection wells.

Single-flash steam units

A single-flash plant is the simplest type of flash plant. Such plants are called 'single-flash' because one flashing process takes place between the reservoir condition (pressurized liquid) and the power plant. The flash usually occurs in the well (but sometimes in the reservoir itself as the geofluid flows toward the well) at the point where the geofluid pressure falls to the saturation pressure corresponding to the temperature and composition of the geofluid. The flash process is similar to a boiling process in that vapour is generated from liquid, but in the case of flashing in a well, this happens essentially without heat being transferred to the fluid and in fact results in a significant drop in fluid temperature. The two-phase fluid received at the wellhead is efficiently separated using cyclone separators just described, and the steam fraction is sent to the turbine. In other respects, a single-flash plant is essentially identical to a direct-steam plant.

Double-flash steam units

A significant improvement in resource utilization over the single-flash steam plant can be achieved by adding a secondary flash process.[5] Instead of being discarded, the liquid that is removed from the separators is subjected to another pressure drop which releases additional steam. The lower-pressure steam is admitted to the steam turbine at an appropriate stage and generates additional power. Except for the extra flash process and the associated hardware, control equipment and piping, the principle of operation of the double-flash steam system is the same as for the single-flash system.

Integrated single- and double-flash steam units

Geothermal fields are usually developed in stages, as in the cases of the liquid-dominated fields at Ahuachapan in El Salvador[6] and at Cerro Prieto I in Mexico.[7] In a typical scenario, during the early stage at least one single-flash unit is built and operated; during the later stage a double-flash unit is integrated with the single-flash unit(s). The integration occurs through the use of the separated liquid from the single-flash unit(s) as the source of low-pressure flash steam (at two pressure levels) for the double-flash unit. The addition of the double-flash unit obviously raises the thermodynamic utilization efficiency of the entire plant since more power is generated with the same amount of geofluid.

Flash-crystallizer/reactor-clarifier units

Geothermal fluids normally carry a wide assortment of dissolved minerals because of the high temperatures involved and the myriad of chemical reactions that can take place between the geofluid and the reservoir rocks.[8] In most fields, the amount and nature of the dissolved solids are such that utilization of the fluids for electric power generation is not difficult. Relatively simple and inexpensive means can be used to control or cope with any potential scaling or corrosion problems.[9] Hypersaline geofluids, however, are found in several fields around the world. Examples include Lac Assal in Djibouti,[10] Cesano in Italy,[11] and the Salton Sea in California, USA.[12]

The concentration of dissolved solids in the fluids at the Salton Sea reservoir ranges from 200 000–300 000 ppm, while the temperature of the fluids in the reservoir may reach 310°C (600°F). The highly corrosive and scale-forming nature of the brines curtailed all attempts to use them in a power plant until the early 1980s. There are now six commercial plants operating in the area with a combined capacity of about 200 MW.[13]

The key to the success of these plants is the use of a flash-crystallizer upstream of the turbine and a reactor-clarifier downstream. The steam is generated in a series of stages using wellhead separators, high-pressure (HPFC) and low-pressure flash crystallizers. The brine from the HPFC is flashed to the LPFC, and the highly concentrated brine from the LPFC is flashed to atmospheric pressure in an atmospheric flash vessel. The vapour fraction is simply vented while the liquid fraction, now highly supersaturated with respect to silica, is fed to a reactor-clarifier (RC) which separates the heavy solids from the liquid. Relatively clear liquid is pumped off the RC and directed to a secondary clarifier (SC). The clear liquid from the SC is then pumped to injection wells. The solids from the RC are sent to a thickener, the outflow from which is divided into two streams: one supplies seed material for the crystallizers, and the other consists of sludge which must be disposed of in an environmentally acceptable manner. At one plant, the sludge is dewatered in a filter system and the product is used in a construction-grades oil cement.[14]

Binary plants

A binary plant is used when it is inadvisable to allow the geofluid to come in contact with the power production equipment, ie, turbines or engines. This may arise because of concerns about scaling, corrosion, or the effects of large quantities of non-condensable gases. Also, if scaling problems occur in the production wells should flashing occur there, then it may be necessary to prevent flashing by means of downwell pumps. Although the use of pumps is not necessary with binary plants, they are currently used in all cases where the reservoir is liquid-dominated.[15] This type of plant is particularly appropriate for lower temperature resources between 120–150°C.

Binary plants which use pumped production wells and which have reinjection wells to receive the spent geofluid are among the most environmentally benign power plants of any type, a major advantage in many environmentally sensitive areas.

Basic binary units

In a basic binary system, the hot liquid enters a vapour generator where it transfers heat to a secondary working fluid (Hence the name 'binary' cycle). The working fluid is chosen to provide a good thermodynamic match to the geofluid, ie, to offer high utilization efficiency, as well as safety and economy. Some of the important characteristics of a working fluid are:

- Thermal stability temperature limit;
- boiling and condensing film coefficients;
- flammability;
- toxicity; and,
- environmental effects, eg, ozone depletion potential.

After leaving the evaporator, the geofluid passes through a preheater section where it heats the working fluid to boiling point (subcritical-pressure conditions) before being discharged to the reinjection wells. A booster pump (or pumps) may be necessary to ensure liquid flow throughout the piping and heat exchangers. As with flash plants, there may be a lower limit on the geofluid discharge temperature or pressure depending on its scaling potential or the thermal effect on the reservoir.

Thermodynamically, the working fluid follows a simple Rankine cycle in a closed loop, passing successively through the preheater, evaporator, superheater (if appropriate), turbine (or other type of expander), condenser and feed pump. Either a subcritical or supercritical vapour pressure may be selected. The condenser may be a water-cooled or air-cooled depending on site conditions. The feed pump consumes a relatively large amount of the gross power compared with the feed pumps in a conventional fossil-fueled or nuclear power station. When this is added to the power requirements for the production well pumps, brine booster pumps, cooling water circulation pumps, and cooling tower fan motors, one finds that a significant fraction of the turbine output, as much as 20–30%, must be spent on parasitics.

Cascaded binary units

The net utilization efficiency of a basic binary cycle can be relatively low because of high parasitic power requirements. Thus, there is ample incentive to seek binary cycles that are more inherently efficient.[16] In this section, we describe two variations on the basic binary cycle that can exhibit higher efficiencies: a dual-pressure system and a dual-fluid system:

Dual-pressure binary plant: In this process the turbine receives the working fluid at two pressure levels. Either two separate turbines or a dual-admission turbine may be used. The condensate pump returns the working fluid to a preheater where it is heated to the saturation point. The fluid is divided into two streams: one enters the low-pressure evaporator and one is pumped to a higher pressure before entering the high-pressure preheater/evaporator. Both evaporators usually operate at subcritical pressures. Typical working fluids include isobutane and isopentane.

Optimized dual-pressure binary plants can have 15–25% higher brine utilization efficiencies compared to basic binary plants for geofluids in the 95-150°C (200–300°F) temperature range. The improvement comes from reducing the thermodynamic losses in the heat exchangers by better matching the heating curve of the working fluid to the cooling curve of the brine.

Dual-fluid binary unit: This system is another way to achieve a similar improvement by incorporating two binary loops, each with a particular working fluid. The key to producing a high-efficiency cycle is to couple the two loops by means of a heat recuperator in which the heat that would otherwise be wasted from the upper loop is transferred to the lower loop in sufficient quantity to provide the heat of vapourization for the lower cycle working fluid. Proper design requires the careful selection of the pair of fluids to match the geofluid characteristics, along with the optimization of the pressures and temperatures for both loops. The Magmamax Unit 1 at East Mesa, CA, USA (the forerunner of the present B.C. McCabe Unit 1) was such a design. The main loop used isobutane and the bottoming loop used propane as the working fluids.

Hybrid plants

The plants described so far may be combined in various ways to form hybrid plants to achieve higher efficiencies or to overcome potential problems related to geofluid characteristics. The following are examples of hybrid plants:

- Direct-steam/binary units; and
- flash-steam/binary units.

Fossil fuels may be used in conjunction with certain geothermal plants, thereby creating 'dual-fuel' plants or fossil-geothermal hybrid plants.[17] These include:

- Geothermal-preheat units;
- fossil-superheat units;
- geothermal-preheat/fossil-superheat units;
- gas turbine topping units; and
- geothermohydraulic units.

ENVIRONMENTAL IMPACTS AND CONTROLS

The environmental impact of using geothermal energy for power production has been the subject of numerous studies and conferences.[18] Impacts may occur in the following areas:

- Air pollution;
- water pollution;
- noise pollution;
- land use;

- water use;
- thermal pollution;
- land subsidence;
- destruction of natural wonders;
- aesthetics; and,
- catastrophic events.

This is a comprehensive list of all possible impacts, but only the first four are significant enough to warrant detailed discussion here. The others will be covered briefly at the end of this section.

Plant emission points

The nature and extent of the impact depends on the type of plant and the resource characteristics. It is important to understand which elements in a plant may contribute to the environmental impact so as to design appropriate controls. During normal operation (ie, excluding emergency conditions), a geothermal power plant may interact with its environment at the following points:

- Silencers at wellheads and powerhouse;
- drains and traps from geofluid pipelines;
- vent from non-condensable gas ejector;
- vapour plume from cooling tower; and,
- blowdown of excess condensate from cooling tower.

For certain plant designs, the following emission points may also be important:

- Condenser cooling water outlet (if using once-through cooling and a direct-contact condenser);
- brine discharge (if not reinjected);
- geofluid exhaust from turbine (for a non-condensing, discharge-to-atmosphere unit;
- outlet streams from gas abatement system (if used).

Finally, the thermal impact on the environment, although not usually thought of as an emission, is conveyed to the surroundings via the cooling tower or the air-cooled condenser, depending on which system is used. We will not deal with the normal impacts associated with the construction phase since these are similar to those for any major power project involving the use of heavy equipment.

Air pollution

Problems may arise if the gaseous elements carried by the steam are discharged to the air. The non-condensable gases consist of carbon dioxide (CO_2) and hydrogen sulfide (H_2S), plus very small amounts of other gases such as methane, hydrogen and ammonia. Emissions of H_2S are considered a problem because of the gas's harmful effects on humans and plants in certain concentrations and its 'rotten egg' odour, detectable at 30 ppb. Strict regulations on H_2S emissions exist at all geothermal plans in the USA. The emissions of CO_2, an important 'greenhouse gas', are not yet regulated, but are a cause for concern.

The amount of gas emitted per unit of electricity generated may be used to rate various methods of power production. Elsewhere I showed that geothermal steam plants have the lowest emissions of CO_2/kWh of electricity than any other type of plant having CO_2 emissions.[19] Geothermal steam plants emit typically only 5% of the CO_2 emitted by a coal plant and about 8% of the CO_2 from an oil plant, per kWh. Table 2 shows the results.

In sparsely populated areas, H_2S emissions are usually not seen as a problem. At many geothermal sites, the air is already burdened with natural emissions from fumaroles, hot springs, mud pots, etc. Where required, power plant H_2S emissions may be drastically reduced by using the best available control technology. At The Geysers plants in northern California, USA, Stretford abatement systems achieve better than 90% reduction of total H_2S emissions. It is noteworthy that the only geothermal plants with H_2S abatement systems are, at present, in the USA.

In principle, one could capture all the vent gas from the non-condensable gas ejector, compress it and reinject it back into the reservoir, as long as the thermal, chemical and physical properties of the formation are favourable. The work required for gas compression, however, could be a significant drain on the plant output. Even in this case, if the geosteam condensate is used as cooling tower makeup, the non-condensable gas which is dissolved in the condensate will be released into the atmosphere with the water vapour plume, unless the condensate is treated chemically.

Finally, binary plants have no gaseous emissions and so do not contribute to air pollution.

Water pollution

Surface waters: These may become contaminated if geothermal fluids are allowed to drain into waterways. High-temperature reservoirs, greater than roughly 230°C (450°F), generally produce liquids containing an extensive menu of dissolved minerals, such as Cl, Na, K, Ca, B, Li, As, F, Mg, Si, I, Rb, Sb, Sr, bicarbonate and sulphate. Not all of these are present in significant concentrations at all sites. Some of these, depending on their concentration, could seriously affect surface waters. Lower temper-

Table 2. Carbon dioxide emissions for various plants.

Fuel/plant type	CO_2 emitted (kg/kWh)
Geothermal	
Binary	0.0
Steam	0.05–0.07
Natural gas	
Combined-cycle	0.41
Steam-cycle	0.45
Simple gas turbine	0.59
Oil/steam cycle	0.68
Wood/steam cycle	0.91
Coal/steam cycle	1.13
Bagasse/steam cycle	1.18

ature reservoirs often yield relatively clean fluids with less than 1 000 ppm of total dissolved solids. Nevertheless, it is good practice to collect all discharge liquids and dispose of them by reinjection. Impermeable evaporation ponds may be used on an interim or temporary basis under emergency conditions.

Ground water: Contamination may occur if the casings in reinjection wells should fail, allowing fluid to leak into shallow aquifers, or if holding ponds are not impermeable. Both of these possibilities can be essentially eliminated by careful design, attention to quality control during drilling and construction, and proper monitoring during operation.

Outside the USA and Japan where reinjection of waste fluids is standard practice, surface disposal of waste fluids is common. It is encouraging that at the new 116.4 MW Ohaaki power plant in New Zealand the waste liquid is reinjected instead of being discharged into the adjacent Waikato River which in fact receives the liquid discharged from the Wairakei geothermal station only a few kilometres upstream.[20] Also, provision is being made to reinject all spent liquid from the 55 MW plant under construction at the Miravalles field in Costa Rica, and at least a portion of the waste brine from the Ahuachapan plant in El Salvador is being reinjected.

Noise pollution

Well drilling generates the most serious noise pollution. During normal plant operation, a geothermal station does not emit objectionable noise. However, under emergency conditions, usually for brief periods, the possibility arises for high noise levels if it is necessary to vent steam. Simple rock mufflers are routinely installed to reduce the velocity (and the noise) of the venting steam. Table 3 shows a comparison of noise levels from a variety of geothermal operations with noises of everyday life. The data refer to plants at The Geysers in California, USA. Even a wide-open, vertically discharging well, one of the worst possible noise sources associated with geothermal operations, when heard from a distance of about one kilometre, is no worse than a typical noisy urban area. Furthermore, the routine noise of plant operation (excluding well drilling, testing, or venting) is practically indistinguishable from other background noises at about one kilometre.

Land use

Geothermal plants must be built on the geothermal reservoirs. Long geofluid transmission lines are not practical because of losses in pressure and temperature. Land is required for the powerhouse and its related equipment such as cooling towers and electrical switchyard, for the well pads, and the geofluid pipelines. Since the latter are normally mounted on stanchions and do not preclude parallel use (such as cattle grazing or agriculture), the land taken out of service for pipe routes is minimal. The well field, however, can cover an extensive area. The total area encompassing all the wells serving the 180 MW Cerro Prieto I plant in Mexico amounts to roughly 5.4×10^6 m^2 or 540 ha.[21] The power house is included within this area. The area actually occupied by the well pads, however, is far smaller, roughly 0.12×10^6 or 12 ha, ie, roughly 2% of the total area. In the case of Cerro Prieto, the space between well pads happens to be unusable because it is barren desert, but in many geothermal fields, the open space is arable.

Geothermal plants require less land per megawatt than competing power plants. In rough figures, a

Table 3. Noise level comparisons.

Noise level (dB (A))	Noise source
120–130	Jet airplane at 30m
114	Geothermal air drilling rig, with 23 kg/s steam entry and no muffler, at 8m
90	Automobile freeway
80–90	Noisy urban area
84	Geothermal air drilling rig, with 25 kg/s steam entry and muffler,. at 8m
82–83	Water cooling towers at 3m
71–83	Open geothermal steam well, vertically discharging, at 900m
73	Geothermal turbine building at 8m
65	Geothermal air drilling rig, with 25 kg/s steam entry and muffler, at 75m
65	Normal speech at 0.3m
50–60	Business office
48–52	Quiet suburban residence
20–30	Wilderness area
0	Hearing threshold

Table 4. Land use for various power plants.

Plant type	Specific area use (10^3 m^2/MW)
Geothermal	
Flash plant	1.2
Binary plant	2.7
Nuclear[a]	10.0
Solar thermal	28.0
Coal-steam[b]	40.0
Solar photovoltaic	66.0

Notes: [a] Based on Boston Edison's Pilgrim Station, Plymouth, MA, USA; plant site only; [b] Based on Salt River Project, Navajo Power Plant, Page, AZ, USA; includes area to be strip mined at Black Mesa, AZ, for 30 years of operation.

single-flash plant requires about 1 200 m^2/MW and a binary plant uses about 2 700 m^2/MW.[22] Table 4 presents a comparison of land use for several common power plants. For example, the 3-unit, 2 258 MW total, coal-burning Navajo plant in Arizona, USA, requires 40 000 m^2/MW, including 30 years of coal strip-mining. A solar-thermal plant for the Mojave desert of California, USA, will need a total of 1.3×10^6 m^2 for an 80 MW (peak) plant, or about 16 000 m^2/peak MW. Accounting for the fact that the plant operates as a solar plant for only 14 hours/day, the land use per average MW soars to 28 000 m^2/average MW.[23] Solar photovoltaic plants require even more land. For plants in the American southwest where the insolation (averaged over 24 hours) is the highest in the USA, namely 0.25 kW/m^2, the collector area alone is 33 000 m^2/average MW, assuming 12% conversion efficiency between photons and electrons. Allowing for 'elbow room' between collectors, doubles the total required land area to 66 000 m^2/average MW.

Other potential environmental impacts

As regards thermal pollution, geothermal plants reject much more heat per unit of electricity generated than other type plants. Table 5 gives a comparison among common power plants. The figures refer to heat discharged at the plant site. If one accounts for the heat dissipated during the winning and transportation of the fuels for the other plants (such as coal, oil, gas or uranium), then geothermal is less disadvantaged. Nevertheless, the waste heat rejection systems for geothermal plants are significantly larger than for comparable sized fossil or nuclear plants.

As regards water use, geothermal steam plants need no external water for cooling purposes since the geosteam is condensed, cooled and recirculated to the condenser. In contrast, a geothermal binary plant has no geosteam condensate and the cooled brine is usually too contaminated for use in a cooling tower without expensive chemical treatment.[24] However, binary plants can be built with air-cooled condensers, thereby eliminating the need for cooling water.

As regards land subsidence, the only noteworthy case is at the Wairakei field in New Zealand where the maximum drop in ground level exceeds 7.5 m and is continuing at an annual rate of about 0.4 m.[25] However, this is confined to a small area away from the powerhouse and has not caused major difficulties.

As regards destruction of natural wonders, care is usually taken to preserve such thermal manifestations as geysers or hot springs wherever they are tourist attractions. Such areas are normally specially designated, as national parks for example, and are off-limits to development. This is certainly true, for example, in the USA, Japan and Costa Rica.

As regards aesthetics, the structures associated with geothermal plants are low in profile and can be designed to blend into the natural surroundings. This is not the case for coal or oil plants which often have stacks as high as 500 feet, nuclear stations with massive containment structures and huge natural draft cooling towers, or wind farms with hundreds of wind turbines mounted on high supports, arrayed on hillsides, in mountain passes or along coastlines.

Finally, there are possible catastrophic events such as well blowouts or earthquakes from induced seismicity. Although well blowouts did occur in the early days of drilling at some fields, for example, at The Geysers (California, USA) and at Wairakei and Ti Mihi (New Zealand), such events are rare nowadays. The likelihood of a blowout is minimized by the proper use of blowout preventer equipment and by following proper drilling procedures. Strict reg-

Table 5. Heat rejected per unit of power output.

Plant type	Thermal power rejected / Electrical power output
Geothermal	
Binary[a]	9.0
Single flash[b]	5.3
Double flash[b]	4.8
Direct steam[c]	4.4
Simple gas turbine	3.0
Solar thermal	2.3
Nuclear	2.0
Coal-steam	1.7
Oil-steam	1.6
Combined cycle	1.1

Notes: [a] Basic cycle; moderate temperature resource, approx 150 C; [b] Resource temperature = 250°C (saturated liquid); condenser temperature = 50°C; [c] Steam temperature = 176°C (saturated); condenser temperature = 50°C.

ulations apply to the drilling of geothermal wells in the USA and other countries. The requirements and procedures in California, where the vast majority of geothermal wells in the USA are located, are particularly stringent.[26]

Induced seismicity is caused when the injection of high-pressure liquid into a fractured reservoir opens fractures and allows adjacent stressed rock masses to slip. Although the reinjection of waste brines involves a similar process, the pressures used are not high enough to cause problems. Studies have shown that the injection (or production) of geothermal fluids does not induce earthquakes; at most, these processes may give rise to microseismic events.

Since many geothermal sites are in areas of steep topography, care must be taken to stabilize all slopes that might be prone to landslides. Natural events of this type can cause serious accidents if the falling rocks damage wellheads or pipes resulting in the release of geofluids.

Even the worst plausible accident at a geothermal plant would be far less serious than, say, at a nuclear station where a major accident has global repercussions, or at a hydroelectric station where the failure of a dam could result in thousands of human fatalities.

COSTS AND INSTITUTIONAL FACTORS

The 330 power plants in operation in 21 countries produce electricity economically relative to competing power plants. Because of the wide variation in geothermal fluid characteristics from site to site, it is not possible to generalize about the costs of field development, plant design and construction, or operation. The cost to generate a kilowatt-hour of electricity depends on the reservoir depth, the fluid temperature, salinity and non-condensable gas content, the size or power rating of the unit, and the type of energy conversion system.

The geofluid and power sales agreements also play important roles. There are several possible arrangements:

- *Single entity:* One agent owns and develops the field, owns and operates the plant, distributes and sells the electricity. This is typical of many countries where the government owns all natural resources and is the sole body responsible for the generation and distribution of power.
- *One field developer, one power producer:* Here one entity holds title to the resource and develops the geofluid supply. This entity sells the geofluid to a different agent who owns the power plant, distributes and sells the power. Such an arrangement is used for most of the units at The Geysers where a number of field operators sell steam to the Pacific Gas & Electric Company.
- *One field developer and power producer, one power purchaser, distributor and seller:* This is the typical arrangement under the US Public Utility Regulatory Policy Act (PURPA) of 1978.[27] The price which the developer/producer receives for the electricity is the so-called 'avoided cost', ie, the cost which the power purchaser (usually a utility) would have to incur if it were to install the capacity to generate the purchased power.

There are many other combinations of these arrangements and many alternative financial structures, some of which are complex involving numerous partners and investors.

For the case of split ownership between the geothermal resource and the power plant, the form of the geofluid sales agreement strongly influences the plant design and economics. Consider two models: Model 1 requires the plant owner to pay the field developer according to the amount of electricity actually generated and delivered to the grid; Model 2 requires the plant owner to pay the field developer according to the amount of geofluid delivered to the plant (at specified thermodynamic conditions). Model 2 provides an economic incentive for the plant owner to make more efficient use of the geofluid than does Model 1. Early steam sales agreements at The Geysers were based on Model 1 and led to relatively simple and inexpensive plants. More recent contracts are based on Model 2 and have led to more costly but much more efficient plants.

The current cost to drill a geothermal well varies widely from field to field: from \$500 000 to \$2 000 000. A typical well can produce about 5 MW. Thus the specific cost of a well ranges from \$100–400/kW.

The specific capital cost to build a geothermal plant (exclusive of well cost) also varies widely depending on the type of energy conversion technology used. Today one finds these costs in the range \$1 000–3 000/kW.

The particular costs for the environmental protection depend on the type and size of the equipment required, which in turn depend strongly on the highly variable resource characteristics. Nevertheless, some estimates can be made for the more common abatement systems.

Where it is necessary to abate the emissions of H_2S, the added capital cost is about \$30/kW for a Stretford-type system.[28] The cost of reinjection wells for the safe disposal of waste brine is in the range of \$50–100/kW. Noise abatement equipment, eg, rock mufflers, are relatively inexpensive on a per/kW basis. Steam venting can be eliminated during turbine trip conditions by incorporating a turbine bypass from the main steam line to the condenser. The capital cost to install such a bypass is about \$18/kW. Assuming that power is available to run auxiliary equipment, this technique eliminates not only noise but also H_2S emissions from unabated steam venting. The annualized cost to build and operate a bypass system is about \$5/kW over the life of the plant.[29]

Since typical geothermal plant capital costs ranged from \$1 000–3 000/kW, the direct costs to abate the most significant potential environmental impacts are not large. There can be indirect costs, however, in the form of lost revenues due to extra outages caused by failure of the abatement systems. For example, having an extra reinjection well on standby may cost \$10–20/kW, and a reduction in capacity factor of, say, ten percentage points would amount to \$85–90/kW in lost annual revenues at a 50 MW plant.

In spite of the long history of geothermal power generation, dating from 1903 in Italy, it remains an unfamiliar technology in many countries. This fact creates a hesitancy to adopt geothermal even in places where it has great potential. Thus, the risks associated with geothermal development tend to become exaggerated. This was no better illustrated than in the early days at The Geysers where the Pacific Gas & Electric Company required Magma Power Company and Thermal Power Company, the field developers, to open the wells to the atmosphere for a period of several months to demonstrate the longevity of the resource before committing itself to construct a power plant. This took place more than 40 years after the successful plant at Larderello began operating.

GEOTHERMAL PROSPECTS

The following countries have excellent potential for developing their geothermal resources to the point of electricity generation by the year 2000: Bolivia; Canada; Chile; Costa Rica; Djibouti; Ethiopia; Guatemala; Honduras; India; Saint Lucia; and, Thailand.

The following countries have interesting prospects and with further exploration may prove to have commercially valuable geothermal resources: Algeria; Austria; Brazil; Burma; Colombia; Domenica; Dominican Republic; Ecuador; Granada; Greece; Haiti; Hungary; Iran; Israel; Jordan; Madagascar; Nepal; Pakistan; Panama; Peru; Portugal (Cape Verde); Spain (Canary Islands); Sri Lanka; Tanazania; Uganda; Venezuela; Vietnam; and, Yugoslavia.

Although it is difficult to quantify these various resources in terms of output, and very few detailed surveys have been carried out, the contribution from geothermal could be significant over the medium term. As an indication, for instance, the USA has a generally accepted potential of around 25 000 MW (electrical) for about 30 to 40 years.

With the emergence of small, modular binary power units as commercially viable plants, many geothermal reservoirs previously thought to be unsuitable for power generation because of relatively low temperatures are now good candidates for development.

CONCLUSION

Geothermal resources are being used today in 21 countries to generate electricity reliably, economically, and safely. For many other countries, particularly in the developing world, geothermal energy could play a major role in meeting the projected demand for electricity. Energy conversion systems are available for use with a wide variety of resources. On the whole, geothermal power plants have far less of an adverse impact on the environment than competing plants. Geothermal reservoirs can produce fluids for long periods of time when properly managed, resulting in long lived base-load power at an economic cost with minimal environmental impact.

The author thanks Ms Joan M. Sincero for her invaluable assistance in word processing which allowed me to meet the publisher's deadline, and Ms Paula J. Sincero for carefully reading the paper and offering many helpful editorial suggestions.

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Part II: Feasibility and System Integration

Chapter 9

Energy Analysis of Renewable Energy Sources

N.D. Mortimer

This paper examines the application of energy analysis to the assessment of renewable energy sources. The basic features, terms, conventions and methods of energy analysis which were established during the 1970s are introduced and the value of energy analysis as a means of evaluating new energy technologies is explained in relation to current concern about resource depletion and global warming. Additionally, the way in which energy analysis can complement conventional economic evaluation is discussed. An extensive summary of results from previous energy analysis studies of renewable energy sources is presented and essential improvements in energy analysis databases to enable progress with new studies are described.

Keywords: Renewable energy; Energy analysis; Global warming

Energy analysis is a means for calculating the total amount of energy required to provide goods or services. Although early forms of this technique appeared in the 1920s and 1930s,[1] the current basis for energy analysis was formulated in the 1970s. During the late 1960s and early 1970s, a number of researchers throughout the world had begun work, often quite independently, on energy analysis. Such work had been encouraged by concern about energy resource depletion and scarcity.[2,3] Further impetus was given to this work by the first oil shock in 1973 and 1974. However, it was not until a workshop, organized by the International Federation of Institutes for Advanced Study (IFIAS), brought together a group of these early researchers, at Guldsmedshyttan in Sweden during August 1974, that a common basis for energy analysis was recommended.[4] A further workshop to consider the relationship between energy analysis and economics took place at Lidingö in Sweden during June 1975.[5]

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Conventions of energy analysis

The IFIAS workshops produced guidelines which provided a set of conventions for energy analysis including basic definitions which characterize the technique, common measures and units of energy-use, agreed methods for calculating results and standard terms for reporting the results. The subsequent conventions of energy analysis have been extensively described elsewhere.[6,7,8] These conventions have changed as different aspects of energy analysis have been emphasized to achieve diverse aims and objectives. However, it is still possible to use the original conventions to consider the energy analysis of renewable sources of energy. The main features of these conventions are summarized here. The most important feature is the meaning of energy in energy analysis. Thermodynamically, energy analysis is the study of free energy changes within a process. Practical considerations mean that energy analysis is mainly concerned with the heat released during the combustion of fuels such as coal and coal products, natural gas and petroleum products although it is possible to take into account the heat generated by nuclear fission reactions and the energy flows available from renewable sources. In most situations, the heat released during combustion is determined from the quoted energy content or calorific value of fuel in question. Although many variants of energy analysis exist, most studies evaluate the total primary energy required by a process. For fossil fuels, primary energy is equivalent to the energy in the fuel immediately after extraction. Although many interpretations are possible for quantifying the primary energy of nuclear power and other sources of primary electricity, such as hydropower, most energy analysis studies assume that this can be equated to the notional heat released by an equivalent conventional coal-fired power station. The energy of labour in any form is usually excluded from energy analysis. The IFIAS guidelines also recommend the use of Système Internationale units of measurements, with the adoption of the joule (J) as the unit of energy. However, since this is a rather small unit of energy in everyday terms, the megajoule (MJ = 10^6J) is more frequently used.

Since the overall aim of energy analysis is to evaluate the total amount of primary energy that is required to provide a given product of service, a systems approach is often applied in subsequent studies. This involves establishing an imaginary boundary around the process under consideration and measuring energy inputs as they cross over this boundary. This leads to the concept of direct and indirect energy inputs. Direct energy inputs arise as the heat released by the combustion of fuels pass over the boundary and are used directly within the system. Indirect energy inputs occur due to the combustion of fuels elsewhere to provide products and services required by the process within the systems boundary. The total amount of energy needed to make one unit of output from the system in question equals the sum of both the direct and indirect energy inputs. This is referred to as the energy requirement if the output is measured in physical terms (for example, MJ/kg), or as the energy intensity if the output is measured in financial terms (for example, MJ/£). When discussing the energy analysis of sources of energy it is particularly important to distinguish between two other terms; the gross energy requirement and the net energy requirement. The gross energy requirement of a source of energy equals the sum of the direct and indirect energy used to provide one unit of output plus the energy content of the original source of energy. The net energy requirement does not include the energy content of the original source of energy. Hence, the net energy requirement gives an indication of the amount of energy from other sources required to obtain energy from the particular source in question. It should be noted that the main result quoted in some energy analysis studies is the energy ratio which is simply the inverse of the energy requirement.

The concept of system boundaries is also helpful in introducing the basic methodologies of energy analysis which can be distinguished into two general approaches; process energy analysis and statistical energy analysis. Process energy analysis involves tracing the energy inputs to all the products and services on which a process depends, described principally in physical terms. Hence, process energy analysis can produce, potentially, very accurate, reliable and specific results. However, to achieve this it is necessary to investigate in detail the energy used in processes which are progressively more removed from the basic system under examination. In contrast, statistical energy analysis relies on sources of statistics that summarize transactions within regional, national or international economies, usually in the form of input–output tables. By using such sources of statistics, all the interconnections between every process within the economy can be determined and the resulting energy inputs can be evaluated. Consequently, it is possible to derive an extensive database of results, typically in the form of energy intensities, quite quickly using statistical energy analysis. However, the results are normally less reliable and less accurate due to the aggregation of information in statistical sources. Although the methods of statistical energy analysis can be used in conjunction with those of process energy analysis, the latter is preferred as a means of obtaining results for specific processes.

Applications of energy analysis

A growing number of energy analysis studies were completed during the 1970s and early 1980s. Some of these studies had different objectives which influenced the particular conventions adopted and governed the meaning and interpretation of subsequent results. To a certain extent, the original conventions reflected the main concerns of the time which were related to fears of mineral resource depletion, focused on fossil fuels. This partly explains the emphasis on primary energy in energy analysis. It further explains the use of calorific values to measure energy since this enabled amounts of energy available from different fossil fuels to be added together, thereby disregarding other differences between these fuels. Such aggregation simplified the derivation and reporting of results which indicated the total dependence of given processes on fossil fuel resources generally. The use of calorific values also enabled the results of energy analysis to form the basis for artificial heat release studies,[9,10] which became quite important at the time because of early interest in the effects of anthropogenic heat release.[11]

However, at the same time, energy analysis was being used in what was regarded as a more significant role. This involved the issue of so-called net energy sinks. Concern about apparent fossil fuel shortages had led to proposals to expand the use of less conventional sources of energy, such as nuclear power, and to develop new energy technologies, mainly involving renewable sources of energy. In many cases, the conventional evaluation of these technologies was thought to be inadequae mainly because their estimated costs were higher than the current prices of conventional sources of energy. However, this approach was being increasingly seen as unreliable due to uncertainty about future prices for conventional energy sources. Hence, it was argued that an alternative means of evaluation was needed which avoided these problems. Energy analysis seemed to offer this alternative because it was based entirely on physical properties which, unlike economic measurements, are not prone to potentially erratic fluctuations resulting from the unpredictable behaviour of the market. In simple terms, energy analysis provided, by means of the net energy requirement, a means of directly comparing the energy input to a new technology with its energy output. Such assessment of the net energy balance was seen as the ultimate test of a new energy technology. If a new technology consumed more energy than it produced so that it had a net energy requirement greater than one, it would not provide any useful contribution to energy supplies and should be dismissed as a net energy sink. Conversely, if a new energy technology could achieve a net energy requirement less than one when energy was in short supply, then it should be adopted for use even if the economic evaluation of its prospects were found to be unfavourable.

However, such simple reasoning is not without problems, especially as regards comparing the energy input with the energy output. The theoretical comparison of the energy input and output must, in practice, be carefully qualified. Although no immediate problem occurs when performing the energy analysis of a technology which produces heat, difficulties arise for technologies with other outputs, especially electricity and liquid fuels for transport. In the case of electricity, for example there are sound thermodynamic reasons why one unit of energy in the form of heat cannot produce one unit of energy in the form of electricity and, hence, the basis of the test that the value of the net energy requirement should not exceed one seems fundamentally flawed. However, a more realistic conclusion would be that energy analysis does not provide results which can be interpreted as an absolute test of viability in all circumstances. Rather, it provides results which can be used comparatively, as will be demonstrated later in the paper. Additionally, it is possible to modify the basic data on fuel consumption which is incorporated into energy analysis so that direct comparisons can be made between energy inputs and outputs.

Energy analysis and economics

Apart from these problems, the early development of energy analysis was also criticized from the perspective of conventional economic theory.[12,13] The main criticism was that energy analysis represented an attempt to promote an energy theory of value as a replacement for conventional economic evaluation especially in terms of allocating resources in finite supply. However, most energy analysts saw the technique as a useful complement to conventional economic evaluation. Energy analysis can provide additional information on which to base decisions of energy resource allocation. Furthermore, the combined use of energy analysis with economic evaluation can correct implicit errors in the latter that can lead to the misallocation of resources. Estimating the likely future costs of a new energy technology is an essential part of the decisionmaking process. However, when such evaluation takes place, assumptions about fuel prices are implicitly incorporated into the calculations. This creates an anomaly in conventional economic evaluation, as can be explained by means of the following simple example.

Assume that the price of electricity from currently conventional sources is equivalent to 1.4 pence/MJ. A new electricity-generating technology has been proposed which incorporates a special material that requires a substantial amount of electricity to manufacture. Further assume an energy analysis study would indicate that 0.8 MJ of electricity are needed to assemble and operate the new energy technology for every 1 MJ of electricity generated. If no other fuels are used then the net energy requirement is 0.8 MJ/MJ. However, such information is not taken into account in conventional economic evaluation which forecasts a cost of, say, 1.9 pence/MJ of electricity produced by the new energy technology. Hence, this suggests that the new energy technology should be economically competitive with conventional sources when the price of electricity rises, in real terms, by about 36%. It might be then concluded that further development of the proposal should proceed so that the new energy technology can be deployed when such electricity price rises materialize. However, the manufacturers' prices for the special material used in the new energy technology incorporates the current price of electricity. When the price of electricity rises to 1.9 pence/MJ, the material will be found to cost more in real terms, thereby resulting in a new forecast price for electricity from the new energy technology of 2.3 pence/MJ which means that it is still uneconomic. In fact, the price of electricity must increase to 3.9 pence/MJ before the new energy technology is competitive, which is a substantially different conclusion from the original result of the conventional economic evaluation. The basis of this anomaly is revealed by combining energy analysis with conventional economic evaluation to derive a simple expression for the forecast price of electricity from the new energy technology;

$$f = n.p. + c$$

where f = forecast price of electricity from the new energy technology (pence/MJ)

n = net energy requirement of the new energy technology (MJ/MJ)

p = price of electricity from conventional sources (pence/MJ)

c = contribution of all other (non-electricity) costs to the price of electricity from the new energy technology (pence/MJ)

In the above example the value of c is taken as 0.78 pence/MJ. Guidance provided by conventional economic evaluation can be even more misleading if the new energy technology in question is, in fact, a net energy sink. Taking the value of any net energy requirement to be greater than one, in this instance, would mean that electricity from the new energy technology would never be economically competitive, no matter how high the comparable price of electricity increased. Despite this, conventional economic evaluation would derive an apparently achievable price forecast for the new energy technology. For example, using a net energy requirement of 1.3 MJ/MJ with the previously assumed values in the above expression results in a forecast price of only 2.6 pence/MJ which, in reality, is not attainable.

These fundamental problems would have been foreseen by energy analysis and would have been resolved by combining the results of this technique with conventional economic evaluation so that the correct advice about the prospects for the new energy technology would be available to decision-makers. In practice, energy analysis has been used to identify potentially misleading conclusions from conventional economic evaluation. Indeed, the technique became a legal requirement in the USA.[14] Other examples of the use of energy analysis in this manner involve the suggested use of uranium from very low grade sources, such as granite and sea water, as an economic option for nuclear power,[15,16,17] the assessment of alternative transport fuels from biomass, such as maize, in the USA,[18] and the appraisal of the wave power research and development programme in the UK.[19]

Summary of results

Having established the essential background of energy analysis, it is now possible to examine some results. Table 1 provides the basis for setting these results presented here in context since it summarizes the total fossil fuel energy required to produce one unit of energy, in the form specified, from a selection of conventional sources of energy. The illustrative results quoted in Table 1 are equivalent to gross energy requirements, apart from the result for electricity from a nuclear power station which is, of course, a net energy requirement. Results from

Table 1. Total fossil fuel energy input for energy supply from conventional sources.

Form of energy	Source of energy	Fossil fuel energy input/unit energy supply
Heating fuel	Coal	1.07[a]
	Natural gas	1.14[a]
	Oil	1.13[a]
Transport fuel	Oil	1.13[a]
Space and water heating	Natural gas	1.78[a,b]
	Oil	1.88[a,b]
Electricity	Coal-fired power station	3.21[c]
	Natural gas-fired power station	3.52[c]
	Oil-fired power station	3.81[c]
	Nuclear power station	0.27[d]

Sources and Notes: [a]Based on UK data for 1974 given in N.D. Mortimer, *The Use of Energy Intensity Multipliers*, Energy Workshop Report No 22, Sunderland Polytechnic, UK, 1981; [b]Assuming a heating appliance efficiency of 60%; [c]From D.A. Pilati, 'Energy analysis of electricity supply and energy conservation options', *Energy*, Vol 2, No 1, 1977, pp 1–7; [d]Pressurized Water Reactor nuclear power station using fuel enriched by gas diffusion methods and uranium from 0.2% grade ores, from data in N.D. Mortimer, *The Energy Analysis of Burner Reactor Power Systems*, PhD Thesis, The Open University, Milton Keynes, UK, 1977.

Table 2. Net energy requirements of heating fuels from renewable energy sources.

Fuel type	Technique	Key specifications	Status	Location	Year of study	Net energy requirement
Dried algae	Cultivation on sewage	–	Experimental	–	1976	2.46[a]
Methane	Anaerobic digestion of livestock waste	Farm operations in warmest period only in temperate zones	Operational	General UK	1976	2.58[a]
	Cultivation and processing of water hyacinth	–	Conceptual	–	1983	0.06[b]
Woody biomass	Silviculture of Loblolly pine	30–90 year rotation, no irrigation no fertilizer, no artificial drying	Silviculture operational	IL, USA	1987	0.02[c]
	Silviculture of mixed hardwoods	60–120 year rotation, no irrigation no fertilizer, no artificial drying	Silviculture operational	IL, USA	1987	0.03[c]
	Silviculture of Autumn olive	2 year rotation, with irrigation, no fertilizer, no artificial drying	–	–	1981	0.08[c]
	Silviculture of Populus	15 year rotation, no irrigation, with fertilizer, no artificial drying	Silviculture operational	MN, USA	1981	0.08[c]
	Silviculture of Populus	15 year rotation, with irrigation, with fertilizer, no artificial drying	Silviculture operational	MN, USA	1981	0.16[c]
	Silviculture of Jack pine	With irrigation, with fertilizer, with artificial drying	–	–	1979	0.20[d]
	Silviculture of Populus	10 year rotation, with irrigation, with fertilizer, with artificial drying	–	–	1979	0.37[c]

Sources: [a]C.W. Lewis, 'Fuels from biomass-energy outlay versus energy returns: a critical appraisal', *Energy*, Vol 2, 1977, pp 241–248; [b]W. Dritschilo *et al*, 'Energy versus food resource ratios for alternative energy technologies', *Energy*, Vol 8, No 4, 1983, pp 255–265; [c]R. Herendeen and S. Brown, 'A comparative analysis of net energy from woody biomass', *Energy*, Vol 12, No 1, 1987, pp 75–84; [d]B. Hannon, 'Energy discounting', *Technological Forecasting and Social Change*, Vol 21, No 2, 1982, pp 281–300.

Table 1 can be used for comparative purposes and, in particular, are appropriate as criteria for assessing the fossil fuel saving potential of different renewable energy sources.

The net energy requirements for providing heating fuel, transport fuel, space and water heating, and electricity from a range of renewable energy sources are given in Tables 2–5, respectively. These net energy requirements represent a selected summary of results from both original energy analysis studies and other published summaries in the relevant literature. In general, the results in Tables 2–5 indicate the amount of primary energy, measured in terms of the energy provided by fossil fuels, required to produce one unit of energy output in the relevant specified form. Although a fairly common basis is assumed for the results given, it should be noted that complete consistency cannot be guaranteed because of the diversity of the energy analysis studies and, in some instances, the lack of detail in the published sources. In some cases, the conventions of energy analysis have been modified for the particular aims of the study in question. There may also be explicit or implicit differences in the choice of system boundaries which, for example, affect the net energy requirements of the electricity-producing renewable sources of energy. These differences concern whether any account is taken of the energy required to construct and maintain the transmission and distribution network which delivers the electricity to consumers and whether adjustments are made for electricity losses in this network. Although some work has been performed on these considerations,[15,20] it is difficult to accommodate them in a general manner because of the relatively site-specific nature of most renewable energy sources. Hence, it is assumed that most of the results given in Table 5 exclude the energy required to construct and maintain the electrical network but may include some allowance for electricity losses in the network.

The information summarized in Tables 2–5 is intended to provide a basic specification of each renewable energy source for which net energy requirements are given. In many instances, this information demonstrates that variations in net energy requirements are due to combinations of differences in technical design and resource conditions. Exam-

Table 3. Net energy requirements of transport fuel (ethanol) from renewable energy sources.

Substrate	Technique	Status	Location	Year of study	Net energy requirement
Cassava	Fermentation	–	–	1976	1.45[a]
Euphorbia	–	Conceptual	–	1980	0.39[b]
Fodder beet	Fermentation	Conceptual	–	1983	0.19[c]
Maize	Fermentation, no use of corn stover as boiler fuel, no energy credit for distillers' grains	Operational	USA	1976	2.03[d]
	Fermentation, no use of corn stover as boiler fuel, no energy credit for distillers' grains	Operational	USA	1979	1.85[d]
	Fermentation, corn stover used as boiler fuel	Proposal	CA, USA	1983	0.94[b]
Straw	Fermentation	–	–	1976	5.26[a]
Sugarcane	Fermentation, with use of bagasse	Operational	Brazil	1976	0.57[a]
Timber	Fermentation via enzymatic hydrolysis	–	–	1976	5.66[a]
	Fermentation via acid hydrolysis	–	–	1976	2.32[a]
	Fermentation via enzymatic hydrolysis, by-product methane used as boiler fuel, energy credit for lignin	Developmental	–	1981	0.07[e]

Sources: [a]C.W. Lewis, 'Fuels from biomass-energy outlay versus energy returns: a critical appraisal', *Energy*, Vol 2, 1977, pp 271–248; [b]W. Dritschilo *et al*, 'Energy versus food resource ratios for alternative energy technologies', *Energy*, Vol 8, No 4, 1983, pp 255–265; [c]J.T. Baines and N.J. Peet, 'Assessing alternative liquid fuels using net energy criteria', *Energy*, Vol 8, No 12, 1983, pp 963–972; [d]M.A. Johnson, 'On gasohol and energy analysis', *Energy*, Vol 8, No 3, 1983, pp 225–233; [e]J.D. Ferchak and E.K. Pye, 'Utilization of biomass in the U.S. for the production of ethanol fuel as a gasoline replacement – II', *Solar Energy*, Vol 26, 1981, pp 17–25.

ples of this would include variations in forest management practices for producing woody biomass for heating fuel (Table 2), in chosen substrate for ethanol production (Table 3), in latitude and system configuration for solar space and water heating (Table 4), and in general resource features, such as geothermal fluid temperatures for geothermal power plants, load factors for hydropower schemes and wind speeds for wind turbines (Table 5). Despite these variations in results, it is possible to compare these net energy requirements for renewable energy sources with those given earlier for conventional sources of energy. The results shown in Table 2 indicate that, apart from the production of dried algae from sewage and the generation of methane by the anaerobic digestion of livestock wastes in temperate regions, the provision of heating fuels from all the other specified renewable energy sources requires considerably less fossil fuel energy than current sources. However, there are problems with the production of ethanol as an alternative fuel for transport, as can be seen in Table 3. The only technically developed processes which require less fossil fuel energy input than current oil products seem to be the fermentation of sugarcane with the use of bagasse and the fermentation of maize, but only if corn stover can be used successfully as a boiler fuel.

In contrast, Table 4 suggests that all the renewable energy space and water heating techniques considered make substantial savings in fossil fuel energy over current methods. Similarly, all the electricity-producing renewable energy sources examined in Table 5 consume less fossil fuel energy than coal-, natural gas- or oil-fired power stations. However, certain renewable energy sources compare relatively poorly with nuclear power in terms of indirect fossil fuel consumption. In particular, these clearly include biomass-fired power plants, geopressurized geothermal power plant, solar-photovoltaic terrestrial arrays, both with and without orbiting reflector systems, solar power satellites with silicon cells, small wind power systems with battery storage and electrical generator back-up and all wave energy devices as configured for the 1982 assessment in the UK. Additionally, all the conceptual hot dry rock geothermal energy systems which assume regular treatment of the artificial reservoir by fracturing are worse or marginally worse than nuclear power in fossil fuel energy terms. However, it should be noted that this comparison is based on a net energy requirement for nuclear power based on current conditions. As demonstrated elsewhere, the net energy requirement for nuclear power can be expected to change in the future; improving with the use of gas centrifuge and laser techniques for uranium enrich-

Table 4. Net energy requirements of space and water heating from renewable energy sources.

Source of energy	Technique	Key specifications	Status	Location	Year of study	Net energy requirement
Geothermal	District heating	–	Operational	Reykjavik, Iceland	1974	0.19[a]
	District heating	Single doublet of wells, 2.5 km pumping distance to heat load	Conceptual	–	1980	0.07[b]
	District heating	Single doublet of wells, 5.0 km pumping distance to heat load	Conceptual	–	1980	0.11[b]
	District heating	Single doublet of wells, 7.5 km pumping distance to heat load	Conceptual	–	1980	0.14[b]
	District heating	Single doublet of wells, 10.0 km pumping distance to heat load	Conceptual	–	1980	0.18[b]
Solar passive (single building)	Direct gain	Latitude 36°N	Operational	Santa Fe, NM, USA	1978	0.05[c]
	Direct gain	Latitude 41°N	Operational	Rochester, NY, USA	1982	0.05[d]
	Greenhouse system	Latitude 36°N	Operational	Santa Fe, NM, USA	1978	0.11[c]
	Greenhouse system	Latitude 44°N	Operational	Midland, MI, USA	1982	0.10[d]
	Trombé wall without night insulation	Latitude 43°N	Operational	Grand Rapids, MI, USA	1982	0.04[d]
	Trombé wall without night insulation	Latitude 36°N	Operational	Sante Fe, NM, USA	1978	0.08[c]
	Trombé wall with night insulation	Latitude 35°N	Operational	Albuquerque, NM, USA	1979	0.02–0.04[e]
	Trombé wall with night insulation	Latitude 43°N	Operational	Madison, WI, USA	1979	0.02–0.05[e]
Solar active (single building)	Air collector with rock storage	Latitude 43°N	Operational	Madison, WI, USA	1979	0.30[e]
	Flat plate air collector with heat pump, storage and hot air distribution system	Latitude 40°N	Operational	Fort Collins, CO, USA	1982	0.20[d]
	Flat plate air collector system	Latitude 30°N	Operational	Washington, DC, USA	1978	0.34[f]
	Flat plate water system with thermo-syphon and daily storage	Latitude 52°N	Operational	Milton Keynes, UK	1975	0.15[g]
	Flat plate water system with thermo-syphon and daily storage	–	Conceptual	General UK	1980	0.09[b]
	Flat plate water system with pumping	Latitude 44°N	Operational	Eugene, OR, USA	1974	0.19[a]
	Flat plate water system with pumping	Latitude 36°N	Operational	Santa Fe, NM, USA	1978	0.45[c]
	Flat plate water system with pumping and daily storage	Latitude 44°N	Operational	Toronto, Ontario, Canada	1980	0.41–0.56[h]

Table 4. Net energy requirements of space and water heating from renewable energy sources (continued).

Source of energy	Technique	Key specifications	Status	Location	Year of study	Net energy requirement
	Flat plate water system with pumping, heat exchanger and hot air distribution	Latitude 39°N	Operational	Colorado Springs, CO, USA	1982	0.59[d]
	Flat plate water system with pumping and daily storage	–	Conceptual	General UK	1980	0.36[b]
	Flat plate water system with seasonal storage, heat exchanger and hot air distribution	Latitude 43°N	Operational	Grand Rapids, MI, USA	1982	0.40[d]
	Concentrating water system	Latitude 36°N	Operational	Sante Fe, NM, USA	1978	0.41[c]
Solar active (multiple buildings)	Flat plate water system with seasonal storage and district heating	Latitude 60°N	Conceptual	General Finland	1983	0.83[i]
	Flat plate water system with seasonal storage, heat pump and district heating	Latitude 60°N	Conceptual	General Finland	1983	0.36[i]
	Concentrating water system with seasonal storage and district heating	Latitude 60°N	Conceptual	General Finland	1983	0.28[i]
	Concentrating water system with seasonal storage, heat pump and district heating	Latitude 60°N	Conceptual	General Finland	1983	0.29[i]
	Solar pond for 20 buildings	–	Conceptual	General USA	1982	0.38[i]
	Solar pond for district heating	–	Conceptual	General USA	1982	0.08[i]

Sources: [a]R.G. Bowen, 'Net energy delivery from geothermal resources', *Geothermal Energy Magazine*, Vol 5, No 2, February 1977, pp 15–19; [b]F. Roberts, 'Energy accounting of alternative energy sources', *Applied Energy*, Vol 6, 1980, pp 1–20; [c]L. Sherwood, 'Total energy use of home heating systems', *Proceedings of a Symposium on Energy Modelling and Net Energy Analysis*, Colorado Springs, CO, USA, August 1978; [d]R.A. Bailey, 'Net energy analysis of four technologies to provide residential space heat', *Energy*, Vol 7, No 10, October 1982, pp 803–815; [e]L. Palmiter and S. Noll, 'Passive, active and conservation: an energetic and economic analysis', *Proceedings of the ISES Conference*, Atlanta GA, USA, May 1979; [f]D.K. Wilcock and A.J. Frabetti, 'Solar energy and resource use', *Solar Age*, January 1978, pp 32–39; [g]P.F. Chapman, *Fuel's Paradise: Energy Options for Britain*, Penguin Books, Harmondsworth, UK, 1975; [h]D.W.O. Rogers, 'Energy resource requirements of a solar heating system', *Energy*, Vol 5, 1980, pp 75–86; [i]P.D. Lund and M.T. Kangas, 'Net energy analysis of district solar heating with seasonal heat storage', *Energy*, Vol 8, No 10, 1983, pp 813–819.

ment and deteriorating with increased reliance on lower quality uranium ores or unconventional sources of uranium.[15,16,17]

Future prospects for energy analysis

The results shown in Tables 2–5 are derived from substantial work on energy analysis during the 1970s and early 1980s. However, few energy analysis studies have been performed recently with the exception of some work on wind turbines. Despite this, the relevance of energy analysis is even more important at the moment, not just because it can be used to improve conventional economic evaluation but also because it relies on data which can be adopted for calculating total CO_2 emissions. Such information is useful for assessing proposed strategies on global warming. Some work has already been undertaken on modifying the previous results of energy analysis as a means of quantifying the indirect as well as the direct release of CO_2.[21] However, at least two developments will be needed to enhance the future prospects of energy analysis.

First, means of providing up-to-date databases of energy requirement and energy intensity results are needed for performing new energy analysis studies.

Table 5. Net energy requirements of electricity from renewable energy sources.

Source of energy	Technique	Key specifications	Status	Location	Year of study	Net energy requirement
Biomass	Wood-fired power plant	–	–	–	1978	0.82[a]
	Eucalyptus tree farm and power plant	–	Conceptual	–	1983	1.13[b]
Geothermal	Condensing dry steam plant	10 × 110 MW, 179°C steam	Operational	The Geysers, CA, USA	1975	0.04[c]
	Condensing dry steam plant	2 × 50 MW, 175°C steam	Operational	The Geysers, CA, USA	1976	0.05[d]
	Condensing dry steam plant	1 × 106 MW, 179°C steam	Operational	The Geysers, CA, USA	1981	0.08[e]
	Double flash plant	2 × 50 MW, 230–315°C brine	Conceptual	Salton Sea, Imperial Valley, CA, USA	1976	0.10[d]
	Double flash plant	1 × 50 MW, 182°C brine	Conceptual	Heber, Imperial Valley, CA, USA	1981	0.23[e]
	Isobutane binary plant	2 × 50 MW, 230–315°C brine	Conceptual	Salton Sea, Imperial Valley, CA, USA	1976	0.14[d]
	Total flow plant	2 × 50 MW, 230–315°C brine	Conceptual	Salton Sea, Imperial Valley, CA, USA	1976	0.09[d]
	Geopressurized flash plant	1 × 25 MW, no methane recovery	Conceptual	Gulf of Mexico, USA	1981	0.35[e]
	Hot dry rock binary plant	1 × 50 MW, 35°C/km geothermal gradient, regular refracturing of reservoir	Conceptual	–	1981	0.37[e]
	Hot dry rock binary plant	1 × 50 MW, 45°C/km geothermal gradient, regular refracturing of reservoir	Conceptual	–	1981	0.29[e]
	Hot dry rock binary plant	1 × 50 MW, 55°C/km geothermal gradient, regular refracturing of reservoir	Conceptual	–	1981	0.26[e]
	Hot dry rock binary plant	1 × 50 MW, 55°C/km geothermal gradient, no refracturing of reservoir	Conceptual	–	1981	0.08[e]
Hydro	Small-scale run-of-river refurbished plant	1 050 kW, 33% load factor	Operational	Elk Rapids, MN, USA	1981	0.10[f]
	Small-scale run-of-river refurbished plant	6 500 kW, 38% load factor	Operational	Waterbury, VT, USA	1981	0.08[f]
	Small-scale run-of-river refurbished plant	3 258 kW, 42% load factor	Operational	Turlock, CA, USA	1981	0.09[f]
	Small-scale run-of-river refurbished plant	1 400 kW, 48% load factor	Operational	Mesa, AZ, USA	1981	0.08[f]
	Small-scale run-of-river refurbished plant	1 325 kW, 65% load factor	Operational	Colliersville, NY, USA	1981	0.12[f]
	Small-scale run-of-river refurbished plant	2 163 kW, 69% load factor	Operational	Fries, VA, USA	1981	0.03[f]
	Small-scale run-of-river refurbished plant	2 800 kW, 83% load factor	Operational	Berlin, NH, USA	1981	0.09[f]

Table 5. Net energy requirements of electricity from renewable energy sources (continued).

Source of energy	Technique	Key specifications	Status	Location	Year of study	Net energy requirement
	Large-scale new peaking plant	45 MW, 21% load factor	Operational	Tims Ford, TN, USA	1981	0.39[f]
	Large-scale new peaking plant	72 MW, 31% load factor	Operational	Melton Hill, TN, USA	1981	0.14[f]
	Large-scale new base load plant	100 MW, 79% load factor	Operational	Nickajack, TN, USA	1981	0.09[f]
OTEC	Ocean thermal energy conversion plant	160 MW Lockheed system	Conceptual	–	1978	0.15[g]
	Ocean thermal energy conversion plant	160 MW Lockheed system, with aluminium heat exchanger	Conceptual	–	1979	0.03–0.06[h]
	Ocean thermal energy conversion plant	160 MW Lockheed system, with titanium heat exchanger	Conceptual	–	1979	0.06[h]
	Ocean thermal energy conversion plant	160 MW JHU/APL system	Conceptual	–	1979	0.05[h]
Solar–photovoltaic	Terrestrial array	10.0 GW, silicon cells	Conceptual	–	1979	0.47[i]
	Orbiting reflector system with terrestrial array	74.2 GW, silicon cells	Conceptual	–	1979	0.98[i]
	Solar power satellite	10.0 GW, silicon cells	Conceptual	–	1979	0.26[i]
	Solar power satellite	10.0 GW, silicon cells	Conceptual	–	1979	0.48[j]
	Solar power satellite	5.0 GW, silicon cells	Conceptual	–	1981	0.29[k]
	Solar power satellite	5.0 GW, gallium–aluminium–arsenide cells	Conceptual	–	1981	0.11[k]
Solar–thermal	Terrestrial distributed collector, point focusing system	–	Conceptual	–	1977	0.24[l]
	Terrestrial heliostats and central tower system	10.0 GW	Conceptual	–	1979	0.15[i]
Tidal	Single barrage	6.3 GW Line 5s scheme, Lavernock–Brean Down	Conceptual	Severn Estuary, UK	1982	0.07[m]
Wind	Horizontal axis machine with battery storage and electricity back-up	3 kW	Conceptual	–	1981	1.92[n]
	Horizontal axis machine	95 kW	Operational	General Denmark	1990	0.08[o]
	Horizontal axis machine	1.0 MW, 46m diameter	Conceptual	General UK	1980	0.16[p]
	Horizontal axis machine	1.0 MW, 53m diameter, 5m/s windspeed	Conceptual	General USA	1978	0.04[q]
	Horizontal axis machine	1.0 MW, 6m/s windspeed	Operational	General UK	1989	0.06[r]
	Horizontal axis machine	1.5 MW, 58m diameter	Conceptual	General UK	1977	0.03[s]
	Horizontal axis machine	3.5 MW, lattice tower	Conceptual	General UK	1980	0.09[p]
	Horizontal axis machine	3.5 MW, reinforced concrete tower	Conceptual	General UK	1980	0.08[p]
	Horizontal axis machine	4.0 MW, 110m diameter, 7m/s windspeed	Conceptual	General USA	1978	0.02[q]
Wave	Salter's Duck	2 GW scheme, 1982 assessment	Conceptual	Outer Hebrides, UK	1982	0.30[t]
	Sea Energy Associates' Clam	2 GW scheme, 1982 assessment	Conceptual	Outer Hebrides, UK	1982	0.31[t]

Table 5. Net energy requirements of electricity from renewable energy sources (continued).

Source of energy	Technique	Key specifications	Status	Location	Year of study	Net energy requirement
	National Engineering Laboratory Oscillating Water Column Breakwater	2 GW scheme, 1982 assessment	Conceptual	Outer Hebrides, UK	1982	0.37[t]
	Lancaster University Flexible Bag	2 GW scheme, 1982 assessment	Conceptual	Outer Hebrides, UK	1982	0.58[t]

Sources: [a]B. Hannon, 'Energy discounting', *Technological Forecasting and Social Change*, Vol 21, No 4, 1982, pp 281–300; [b]W. Dritschilo *et al*, 'Energy versus food resource ratios for alternative energy technologies', *Energy*, Vol 8, No 4, 1983, pp 255–265; [c]R.G. Bowen, 'Net energy delivery from geothermal resources', *Geothermal Energy Magazine*, Vol 5, No 2, February 1977, pp 15–19; [d]L. Icerman, 'Net energy analyses for liquid dominated and vapour-dominated hydrothermal energy resource developments', *Energy*, Vol 1, 1976, pp 347–365; [e]R.A. Herendeen and R.L. Plant, 'Energy analysis of four geothermal technologies', *Energy*, Vol 6, 1981, pp 73–82; [f]M.W. Gilliland, J.M. Klopatek and S.G. Hildebrand, 'Net energy: hydroelectric power and summary of existing analyses', *Energy*, Vol 6, No 10, 1981, pp 1 029–1 040; [g]A.M. Perry, G. Marland and L.W. Zelby, *Net Energy Analysis of an Ocean Thermal Energy Conversion System*, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, TN, USA, 1978; [h]R. Harrison and G. Jenkins, 'Energy analysis and the technical forecasting of the viability of solar energy technologies', *Energy for Industry*, Pergamon Press, Oxford, UK, 1979; [i]R.C. Enger and H. Weichel, 'Solar electric generating system resource requirements', *Solar Energy*, Vol 23, 1979, pp 255–261; [j]R.A. Herendeen, T. Kary and J. Rebitzer, 'Energy analysis of the solar power satellite', *Science*, Vol 205, No 4 405, August 1979, pp 451–454; [k]C.C. Frantz and A.B. Cambel, 'Net energy analysis of space power satellites', *Energy*, Vol 6, 1981, pp 484–501; [l]A.J. Frabetti *et al*, *Application of Net Energy Analysis to Consumer Technologies*, ERDA 77-14, Development Sciences Inc, USA, 1977; [m]F. Roberts, 'Energy accounting of River Severn tidal power schemes', *Applied Energy*, Vol 11, 1982, pp 197–213; [n]B.N. Haack, 'Net energy analysis of small wind energy conversion systems', *Applied Energy*, Vol 9, 1981, pp 193–200; [o]E. Grum-Schwensen, 'The real cost of wind turbine construction', *WindStats Newsletter*, Vol 3, No 2, Spring 1990, pp 1–2; [p]F. Roberts, 'Energy accounting of alternative energy sources', *Applied Energy*, Vol 6, 1980, pp 1–20; [q]D. Bain, 'Wind energy – net energy and jobs', *Wind Power Digest*, Spring 1978, pp 46–48; [r]G. Jenkins, Sunderland Polytechnic, UK, private communication, February 1989; [s]W. Devine, *Energy Analysis of a Wind Energy Conversion System for Fuel Displacement*, ORAU/IEA(M)–77–2, Institute for Energy Analysis, Oak Ridge Associated University, Oak Ridge, TN, USA, 1977; [t]G. Jenkins, 'Energy analysis of some wave energy systems', PhD Thesis, Sunderland Polytechnic, UK, April 1984.

The information incorporated into the results of previous studies was obtained from databases compiled almost exclusively during the 1970s. Although a very extensive collection of energy requirements, derived by process energy analysis, is available, these results also relate to practices common in the 1970s.[8] Obviously, these practices will have altered since then. Changes will also have affected national statistics used to derive energy intensities by means of statistical energy analysis. Existing databases of energy intensities relate to the UK in 1963 and 1968[22,23] and to the USA in 1963, 1967 and 1972,[24–27] in particular. Although some more recent statistical energy analysis has been performed,[28] there is an obvious need for producing up-to-date collections of generally applicable energy intensities and energy requirements. The continued use of energy analysis will also depend on generating such databases regularly in the future and it would be particularly helpful if such databases could contain disaggregated information on fuel consumption and use, which leads to the other important development needed for the future of energy analysis.

In the past, basic fuel data were commonly aggregated to obtain results represented by single numbers. Although the attractions of this approach are obvious, it limits the application of results and can obscure their interpretation. Apart from simple work on energy analysis, it would be helpful to retain as much information as possible by expressing results in terms of the amount of energy used in a given process, distinguished by fuel type (for example, coal, natural gas, oil, electricity, etc) and by fuel application (for example, process heating, space and water heating, motive power, lighting, electrolysis, etc). This would enable energy analysis to be used in a more flexible and sophisticated manner as well as extending the scope of the technique. It would allow assumptions about energy supply and energy-use, especially in relation to changing patterns of fuel use and the potential effects of energy efficiency measures, to be altered. Additionally, the disaggregated information could be converted for purposes other than the current assessment of fossil fuel-use and heat release. One particularly relevant alternative application would be for quantifying CO_2 emissions and some work on this, using the 1984 input–output tables for the UK, is presently underway at Sheffield City Polytechnic. Previously, the proposed disaggregation of information necessary for extending the use of energy analysis was correctly regarded as too complex. However, this problem can now be overcome due to the availability of suitable computing power and appropriate software packages such as spreadsheets.

The author would like to acknowledge the assistance of Garry Jenkins of the Renewable Energy Centre of Sunderland Polytechnic in preparing the summary of energy analysis results for this paper. Any errors or misinterpretations in this paper are, however, the responsibility of the author alone.

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Chapter 10

Integration of Renewable Electricity Sources

M.J. Grubb

The variable and energy-limited nature of electricity output from many renewables impede their use in small-scale applications. The drawbacks are much less when renewables are connected to integrated power systems. Indeed when capacities are small relative to the total system, renewables can often be more valuable than conventional sources, and very large capacities can in general be accommodated without incurring major operating penalties. Also, the characteristics of different variable and energy-limited renewable sources are usually complementary, and current trends in power system development will further ease their integration. With the possible exception of very large-scale use of photovoltaics, it seems most unlikely that the special characteristics of renewable electricity output will significantly limit their use, provided that their role in power systems is properly managed and reflected in the tariff arrangements for renewable generators.

Keywords: Renewable energy; Integration; Power system economics

The output from most renewable sources of electricity differs from most conventional power sources. Sources such as wind, solar, wave and tidal energy, are usually 'variable': their output follows the natural fluctuations of the weather and tides.[1] Even hydro and biomass electricity differ from conventional thermal plants, in being limited by the amount of energy available rather than the generating capacity installed. As such renewable energy sources receive increasing interest – both in the short term because of the rapid economic advances in wind energy especially, and for the long term because of their potential strategic and environmental importance – questions about the value of such sources when integrated on power systems are attracting growing attention.

It has been widely assumed that the variable nature of many renewables poses a serious obstacle to their deployment, and would necessitate storage which could be costly, The International Energy Agency (IEA) stated that the special characteristics 'present a limitation to expanded utilization of some economic renewable energy technologies.'[2] A generally positive report by the US DoE stated that 'energy storage, or a supplemental source of energy, may have to be provided to make solar energy marketable'.[3] McLarnon and Cairns state that 'energy storage is critical to intermittent energy systems'.[4] Such assertions appear reasonable, but they are assumptions, not conclusions. Serious analysis reveals them to be largely without foundation.

This paper examines the extent to which the special characteristics of renewables affect the value of their output. What penalties do variations and limited predictability impose on the operation of the rest of the system? How much backup capacity is required to maintain a reliable system, and how does this affect the economics? How much benefit might be obtained from greater geographical and source diversity, and how might this compare with the additional transmission requirements? More generally, how would incorporating renewables affect the optimal plant mix and system operation in the longer term, and to what extent might the special characteristics of many renewables constrain their feasible long-term contribution?

These are not new questions, many of them having been examined to some degree in various modelling and other studies, particularly since the substantial efforts undertaken by the US Solar Energy Research Institute at the beginning of the 1980s.[5] This paper examines the key factors which affect the value of variable and other renewable electricity sources on power systems, places this in the context of power systems as they are now evolving, and considers the potential role of various combinations of renewables on such systems.

Before embarking on this, it should be empha-

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sized that, as for many other aspects of renewable sources, few generalizations hold for all renewables; indeed, the characteristics of each are very distinct, and can also vary according to the location and pattern of their deployment. A number of important renewable sources are not significantly variable. Biomass is one obvious example. Large-scale hydropower taps a somewhat variable source (river flow) but with a large inherent storage capacity – usually with inter-seasonal capability, and sometimes enough to smooth across inter-annual variations. Small-scale hydro schemes follow variations in river flow more closely, but are usually still associated with a limited storage capacity. Ocean thermal energy is a genuinely constant source; so, often, is geothermal energy (which is usually considered as a renewable source, although generally it is not because heat is extracted faster than it is replaced).

Some of the technologies for tapping direct solar energy can also smooth out some of the variations. Solar ponds, in which solar-induced temperature differences between layers in salt ponds are used to drive steam turbine cycles, may produce relatively smooth output, with a storage capacity ranging from hours to days. Central 'power towers' in which mirrors focus sunlight on a central boiler, may also give a few hours inertia. The dispersed thermal systems developed by Luz International for California, in which parabolic reflectors heat oil to drive a steam turbine, adopt a different approach; natural gas is used to provide an alternate heat source for the turbine for occasions when peak demand coincides with periods of low solar radiation.[6]

There are, however, important renewables which are inherently variable and which cannot readily have storage or other backup integrated with the design. Outstanding among these are photovoltaics, which arguably offer the greatest long-term potential of any of the renewable sources, and wind energy, which is among the most developed of the major non-hydro renewables. Wave energy and tidal energy, which may also offer important potential on some systems, are also inherently variable.

It is with the economics of such sources when integrated on large power systems that most of this paper is concerned. Before addressing this, it is useful to consider first the scope for and issues raised by other possible applications, and broader issues of power system economics.

Isolated supplies and small systems

Many renewable sources are already used, or under consideration, for applications where the demand is too small to be met by large conventional power stations, and which cannot readily be connected to existing grids.

At the extreme are various mobile applications, such as caravans, and applications which are too small to justify even short extensions from electricity grids. Windmills have been used for centuries to provide mechanical power, and in addition to continuing widespread use for irrigation pumping they are now used for various forms of remote electrical power. Photovoltaics (PVs) tend to be best suited to the smallest modern electrical uses, because the unit costs depend little on the scale of application. Storage is usually required, but for small applications the costs are modest, partly because PVs can generate at least some power every day. In addition to various familiar micro-electronic applications, Hill[7] reports that even in a country such as the UK there are many possibilities: PV is frequently the most cost-effective option for communication repeater stations, cathodic protection of various structures, motorway signs and telephone points, boats and caravans, as well as isolated dwellings: 'it is now cheaper to install a PV lighting unit in a shed at the bottom of the garden rather than pay to have a mains cable'.[8] In developing countries the potential applications are much larger still, and PV can provide invaluable services for mobile or remote refrigeration, lighting, etc.

In addition, there are some homes in most countries which are far from grid supplies. In such applications the cost of the renewable source itself may indeed be a secondary factor; the choice may be driven largely by the competition between the cost of adequate storage against that of the copper lines for connecting to the nearest alternate source of power. Though the applications are small, in total they can be considerable even in countries with developed grid systems; the Californian Pacific Gas and Electric utility has estimated that isolated supplies might total up to 5% of the electricity already supplied through the grid system, and that exploiting these with stand-alone renewable units could yield considerable savings over the costs of continuing to extend the grid.[9]

A different situation is presented by rather larger isolated uses, for example on small islands or isolated villages or farms. In many tropical and subtropical regions, PV may be suitable, but as evening lighting is often a main load, considerable storage may be required. For many island supplies, wind and perhaps shore-based wave machines are promising. Wind is also frequently better suited than PV inland in temperate zones, for example in mountain villages, though combinations with PV can also be of interest.

Currently, such loads are usually met using diesel generators, and the primary interest in renewables is to offset the high costs of running diesel. However, diesel sets are generally cumbersome in operation, with considerable losses incurred in startup, shut down, and part loading (ie running below design capacity), and with many constraints on the rate of change in output and minimum stable output levels. Together with the high variability of output from individual wind turbines, for example, this can result in considerable operating penalties on wind–diesel systems, and the economics can depend heavily upon the development of sophisticated control strategies. In one successful application on Fair Isle, with a single diesel set, some loads are controlled automatically to minimize the need for operation of the diesel set (eg fridges are placed on circuits which can be interrupted for short periods).[10] As compared with the previous diesel-only operation, large savings, together with improved quantity and quality of supply, have been obtained. Other applications make use of small hydro schemes to provide a degree of storage and control, further reducing operation of the diesel set.

On larger diesel systems, the operation and role of renewable sources begins to have more in common with that of large power systems. Some diesel sets are always running, and the system operators need to adjust their scheduling to take account of additional variations imposed by the renewable input. Good control can again yield considerable savings,[11] but the high variability of wind input, for example, combined with the poor operating characteristics of diesel sets means that the renewable contribution may be severely limited if large operating penalties are to be avoided.

Successful applications of renewables for isolated and small-scale supplies can undoubtedly be of great value to those who benefit directly from them, and they offer a market which is very significant for the renewable energy industries. PV, indeed, has largely developed because of such 'niche' markets, and the frontiers of such markets are steadily expanding. But in terms of global electricity supplies, and their economic and environmental impact, such applications are likely to remain marginal compared with the energy provided through large-scale power systems.

One way in which renewable electricity sources could in principle make a large global contribution would be if they could find a way into the transport market. Producing hydrogen from PV in desert areas has been proposed as one of the most promising ways of displacing oil in transport, with long-run costs estimated at $1.70 to $2.40/gallon of gasoline equivalent.[12] An alternative transport application might be to use stand-alone renewable (probably PV) units at car parks, homes, garages or automated roadside filling points, to charge batteries for electric cars or perhaps to generate hydrogen for hydrogen vehicles. This would bear closer analysis as one of the long-term options for moving away from gasoline, but is highly speculative and clearly faces important economic and infrastructural hurdles.

With this exception, renewable electricity sources can only make a major contribution to resolving energy dilemmas if they can compete when integrated into large power systems. The rest of this paper focuses upon the issues this raises.

System operation and the role of different plant types

Electric power systems comprise a wide variety of generating plant types. One key distinguishing feature is the ratio of capital costs to operating costs. For meeting peak loads, plants which are cheap to build but relatively expensive to run are most suitable, because they are not required to run very often. For meeting baseload demand, capital-intensive plants with much lower operating costs are more appropriate. In practice, the great majority of investment in power systems have been associated with plants for baseload operation.

Only one generalization appears to apply to almost all renewable electricity sources, and that is that they are capital intensive, with relatively low operating costs. Even for biomass plantations, the major costs could be associated with establishing the plantation, and investment in the machinery to harvest and utilize the product. Perhaps the only exception is that of waste utilization, where most of the costs may be associated with gathering and sorting the waste, as opposed to leaving it uncollected. With this exception, all renewable sources are best suited for meeting baseload demands.

Most, however, differ from fossil-fuel and nuclear baseload plants in important ways. Such conventional thermal power stations are *capacity limited*, with the output limited by the rated capacity of the plant. These contrast with *energy limited* plants, which are unable to generate permanently at the maximum capacity because the total energy available is limited. Hydropower stations are the classic example; many biomass systems, particularly those based on agricultural wastes or dedicated plantations, would

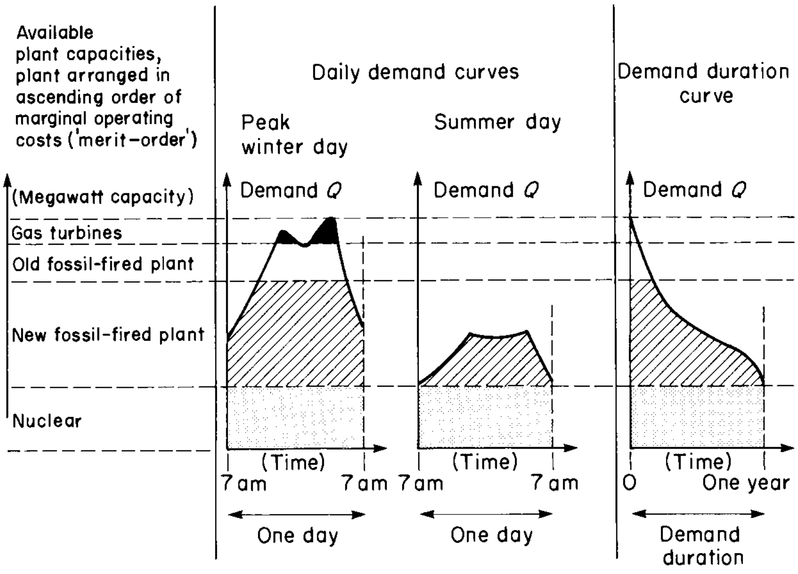

Figure 1. The load duration curve and merit order.
Source: R. Turvey and D. Anderson, *Electricity Economics*, Johns Hopkins, Baltimore, MD, USA, 1977.

also be of this type. Electricity storage is a special case of energy limited plants, in which the energy is derived from conventional baseload power stations at times of low demand. *Variable* power sources, in which the output is determined directly by variations in the energy input, form a third distinct class.

At present, many power stations are composed almost entirely of capacity-limited plants. If the complications introduced by the second-order effects of system dynamics (eg plant startups and shutdowns, operating reserve, etc) are neglected, such plants can be stacked in a simple 'merit order' of operation, in which those with the lowest operating costs are used as much as possible, with those of higher operating costs brought on-line progressively as the capacity of cheaper plants is exceeded. This defines the merit order, which runs from baseload plants through to peaking plants.

The key characteristics of the demand and generating costs can then be usefully represented in terms of the load duration curve (Figure 1), which illustrates the duration for which the load exceeds a given level. With power (load) on one axis and duration on the other, the product, and hence the area under the curve, represents the total energy supplied within the time period under consideration. Going up the y-axis represents steadily declining durations of supply, so that plants can simply be stacked in merit order under the load duration curve to estimate the energy supplied by each, and hence the operating costs.

Energy limited plants introduce significant complications. Although hydro stations may operate more cheaply than any other plant on the system, there is usually not enough energy available for them to be run at full capacity all the time. Operating at a constant but reduced output does not make full use of the capacity, which can be used preferentially to displace more expensive fuels. In fact it is readily apparent that the best use of energy from hydro or other limited energy plants is to operate them at full power whenever the marginal fuel cost on the system exceeds a given level – with that level determined by the amount of energy available. In other words, the greatest value is generally obtained by inserting energy limited plants at a fixed point in the merit order of capacity-constrained plants, such that all the energy available is used at or near the full plant capacity (Figure 2).

Uncertainties in the amount of energy available and in electricity demand over a given period, combined with various aspects of system dynamics (eg the additional value of hydro plants for providing short-term operating reserve – an issue discussed later) complicate this picture, but the principle remains valid. As a result, energy from energy limited plants is more valuable than that from other baseload plants, because of the additional value derived from the flexibility in deciding how the additional capacity is used. Fuller discussions of the management and economics of hydropower are given elsewhere.[13]

As well as hydro, this would apply to biomass-electricity plants. The significance of this factor

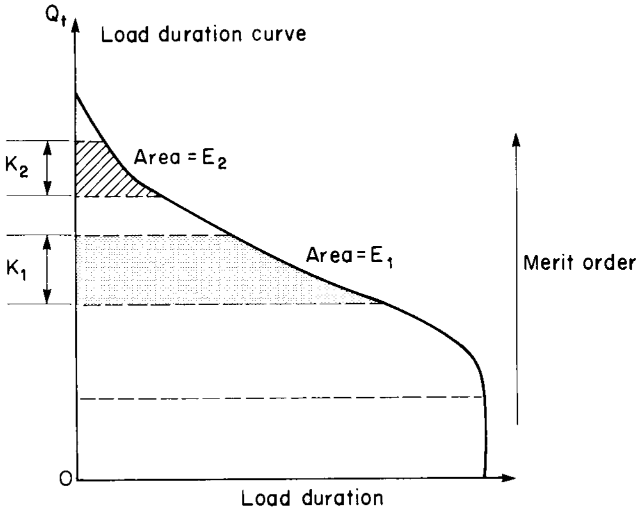

Figure 2. Operating strategy for energy limited plants.

Note: The plants are inserted in the merit order of thermal operation so that all the energy (E_1, E_2) can be delivered at the full plant capacity (K_1, K_2), excepting any spare reserved for system regulation. In this idealized example the second energy limited plant has a high ratio of capacity to energy: it displaces mosly peaking fuels, and makes a relatively large contribution to system reliability.

depends upon the incremental costs of adding extra generating capacity to the energy limited plant relative to those of increasing the total amount of energy available (discussed below in considering different combinations of renewables), the structure of the rest of the system, and the pattern of electricity demand. In general energy limited plants become relatively more valuable for systems which have a wide range of thermal plant generating costs, and a demand which varies widely in the period covered. The same remarks apply to electricity storage plants, which with minor modifications can be considered as energy limited plants with an 'optimal' energy content determined by system conditions (ie, by comparing the cost of using the marginal baseload plant to charge the store (usually overnight) against the value of generation the next day, after allowing for the losses in the conversion process).

Variable power sources form the third distinct class of plants. Almost without exception, their operating costs are lower than those of any thermal plants on the system. Hence, their power would as far as possible be used whenever available, to reduce the fuel-use in fossil-fuel plants: like nuclear power, variable sources would operate at the 'top' of the merit order.

In these conditions they reduce the demand upon thermal units in the system, and indeed it is usually simplest to think of variable sources as a negative load. Since load can vary by nearly a factor of two in its daily cycle, and cannot always be accurately predicted, the variable and perhaps unpredictable nature of such sources does not pose any radically new problems for power system operation. Figure 3, which shows the output which would have been expected from very large capacities of wind and tidal energy alongside the Central Electricity Generating Board (CEGB) demand over the same period, serves to emphasize that source variability needs to be considered in the context of the varying demand which it helps to meet. Dispersed wind varies less rapidly than demand, tidal more rapidly. Figure 4 shows the net effect of subtracting both these series

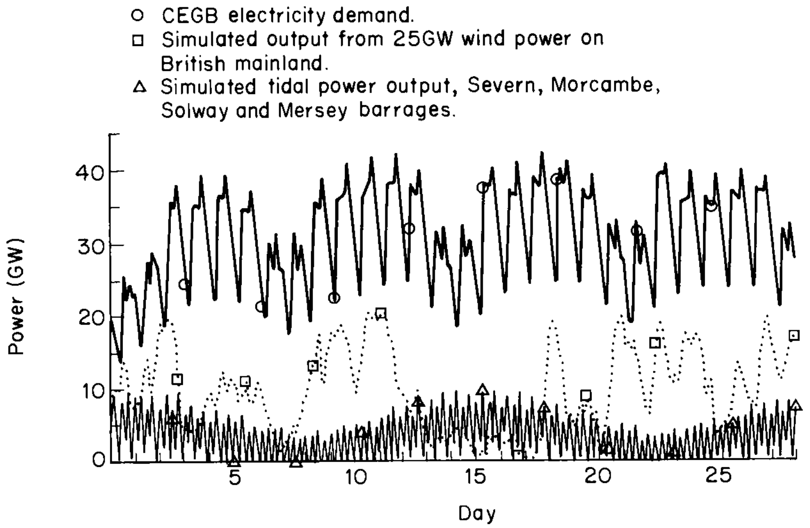

Figure 3. Electricity demand and potential output from wind and tidal sources in Britain (January 1978 data).

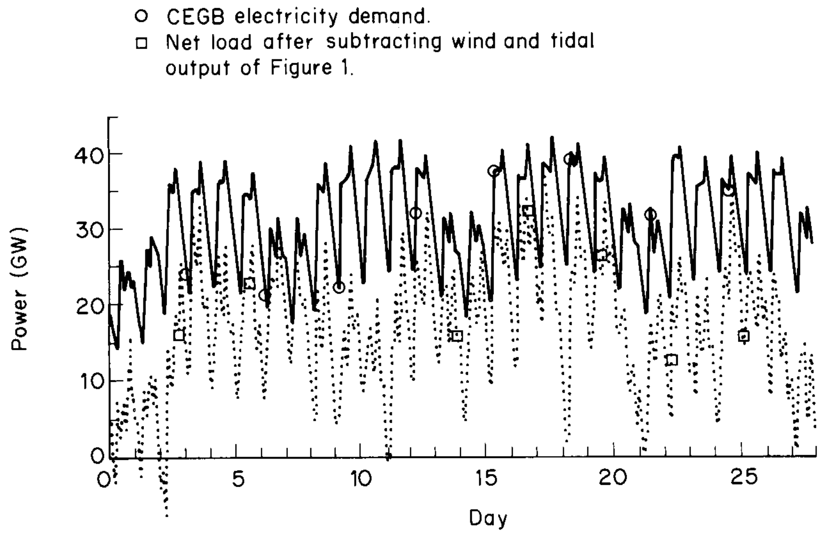

Figure 4. Residual demand to be met by thermal system after including wind and tidal sources in Britain (January 1978 data).

from the demand, leaving a much reduced net load to be met by the thermal plants.

The important question is: how do these variations affect the economic value of variable sources? To address this it is useful to start by disposing of two myths: first, that variable sources are best suited to small-scale or isolated electricity supply; and, second, that electricity storage is needed to exploit them to any substantial degree.

From a technical viewpoint, variable sources are far better suited to large power systems than to localized supplies. On small systems, just one or a few units, clustered on one site, may generate a substantial fraction of the total energy. The output may then be very variable, sometimes fluctuating widely within a few minutes. As noted above, the rest of the system might well amount to just a few diesel stations, which then may have to alter their output rapidly to follow the changes, with individual units repeatedly shut down and restarted, wasting fuel and increasing maintenance requirements.

By contrast, a large system can often take advantage of natural diversity in variable sources. Significant capacities of wind energy, for example, would involve many wind turbines, spread out between different sites, and this would smooth the overall output greatly. The variability is reduced, predictability increased, and overall distribution becomes much more favourable with far fewer occasions of near zero or peak output. Appendix 1 discusses how these effects may be roughly quantified, and illustrates this with examples of wind energy in Britain. Diversity would not of course remove diurnal variations in PV output, but it would still help to smooth more rapid weather-related variations.

Furthermore, there is much more natural reserve on large systems, with many thermal generating units connected at any one time. Such systems will mostly also have some units – hydropower or gas turbines – which can respond very rapidly to changing conditions. So all round, the problems of integrating variable sources are much reduced when the are connected to large power systems.

Bulk storage becomes far less important for much the same reasons. Since the fluctuations of variable sources combine with those of the electricity demand, storage can only usefully be considered in relation to the whole of the power system. Storage is valuable if it can often be charged using cheap energy (eg at times of low demand or high output from variable baseload sources) and discharged to save expensive fuel (eg at times of high demand and low output from the variable sources). But if variable sources are well diversified on a large system, they may not greatly increase the frequency of such opportunities unless the capacities are very high. Except in such cases, additional storage is unlikely to be very important; backup may be required, but as discussed in the next section there are many other options for providing this.

This is just as well. Large-scale electricity storage – usually in the form of water pumped up and down a mountain – is expensive, and about 20% of the energy may be lost in passing through the store, due to inefficiencies in charging/pumping and generating. On small systems the high cost of alternative fuels (and hence potential savings) may make such costs and losses justifiable. On large power systems, with much lower generating costs, renewable sources would be virtually ruled out if extensive storage really were an essential component. Of course, increasing capacities of variable sources may increase the value of storage, and vice versa, but storage is in no sense a central element. Since it greatly complicates the analysis and behaviour of the power system and this obscures the main issues, most of this paper will make the conservative assumption that storage is too expensive to be of relevance in assessing the large-scale integration of variable sources.

This poses an immediate question to many observers. If variable sources are not combined with storage, they cannot be relied upon to generate power at times of high demand, when it is most needed. Other backup is apparently required. Doesn't this itself impose a serious penalty?

The capacity question

Some renewable sources can reliably produce power at times of peak electricity demand. In addition to energy limited plants, which can be scheduled to generate maximum power at such times, the classic example is that of solar electricity on systems which have peak demand driven by air conditioning loads, which are greatest when the sun is bright. In a few areas, the strongest winds are driven by local, solar-induced thermal gradients and happen to coincide with a solar-driven peak demand. When such strong and dependable correlations occur, it is clearly very convenient, and adds somewhat to the real value of the source to the system. But such correlations can rarely be relied upon. As noted above, the Luz thermal systems achieve the same result by use of a cheap gas backup; but such opportunities are again limited.

In most cases variable sources are not necessarily available for demand peaks. In some temperate countries (eg the UK) there has been some debate over correlations between wind and electricity demand. There certainly can be some correlation – winds increase the thermal loss from buildings, for example – but there are many other factors. High demand can also coincide with periods of very cold, clear calms. Surprisingly, it is still not possible to be sure of the overall relationship at peak demands: statistical evidence from 10 year's data in Britain is still ambiguous.[14] Though there is a substantial seasonal correlation, wind energy *in winter* in Britain is very weakly correlated with demand. Other sources, such as wave and tidal energy, also have low correlation with peak demand during the peak season.

Nevertheless, such sources can save thermal capacity. Since no generating station is completely reliable, there is always a finite risk of not having enough capacity available. To keep this risk low, a large margin of plant capacity over maximum expected demand, typically 20–30% excess capacity, must be maintained. Variable sources may be available at the critical moment when demand is high and many other units have failed, so they reduce the overall risk of failure and allow the thermal plant margin to be reduced. In fact it can be shown that when the capacity of any independent source is small relative to the rest of the system (low system penetration), its 'capacity value' is independent of its actual reliability, and equals that of a completely reliable plant generating the same average power at times when the system could be at risk. One proof of this result is given in Appendix 2.

As the capacity of any variable source rises, it becomes progressively less valuable for saving thermal capacity, because there are times with little or no output however large the capacity. The savings, however, can in total be considerable. Figure 5 shows the approximate savings in thermal capacity which dispersed wind energy in England and Wales might allow as the wind capacity rises. Wind energy contributes as much as other sources, relative to the mean power, for the first few thousand MW, but falls off thereafter. At maximum, about 5.5GW of thermal capacity might be saved (about 10% of the total thermal capacity). This still implies a margin of thermal plant capacity over peak demand, but the degree of excess would be reduced to 10–15%.

The relatively high capacity value reflects in part the benefits of the large diversity available, which makes periods without any wind at all in winter quite rare; results for the Netherlands show a proportionately somewhat smaller capacity credit (differing methodologies and wind turbine and resource characteristics may also contribute).[15]

Suitable combinations of renewable sources may yield greater thermal capacity savings. When two variable sources vary independently, their capacity contribution may also be largely independent, and additive. A still greater effect is obtained if different variable sources are directly complementary, for example, solar and wind energy are frequently, because strong winds tend to be associated with overcast conditions. In thermally-driven wind regimes, the strongest winds may also occur towards or after sunset. Indeed in some areas of California it

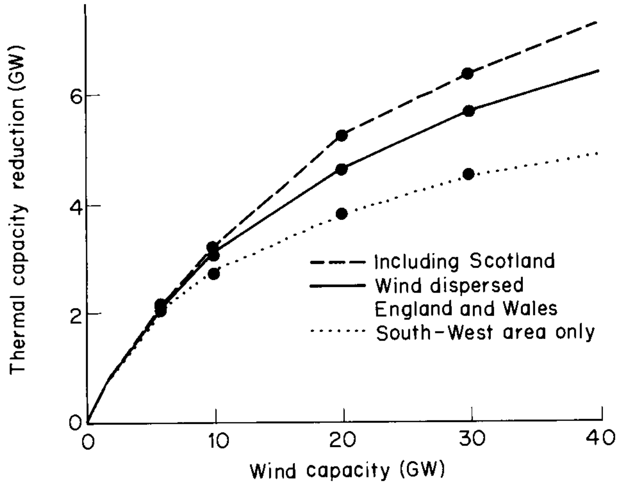

Figure 5. Thermal capacity displacement with increasing system penetration, illustrative estimate of wind energy in Britain.

has been realized that winds pick up as the sun is going down, and that the combination of wind and solar provides a fairly reliable input across the period of high demand, which spans from the early afternoon to early evening.

However, despite the concern and interest which such issues and opportunities raise, capacity credit is usually of much less economic importance to the system than many assume. The value of capacity credit itself is the marginal cost of ensuring that the available capacity is sufficient to meet demand in peak periods. Some systems may already have substantial capacities of old, inefficient plants on the system, and keeping them serviceable for peak demands instead of retiring them may be a cheap way of ensuring adequate capacity. Many industrial users, especially, have their own backup capacity, which could provide cheap emergency capacity if it could be tapped. This might be a special example of ways in which more sophisticated load management of various forms, could also help to reduce the costs associated with peak demands.

Even without such options, the marginal costs of adding 'firm capacity' for meeting peak loads is modest. Industrial gas turbines can provide capacity at one-third to one-fifth the cost of most baseload plants. Such units can be expensive to run (though with the advent of modern gas turbine cycles this is less true than it used to be), but by definition peaking plants are only used occasionally so matter little. Even if there were no capacity credit for variable sources, building gas turbines for backup would generally add less than 20% to the estimated complete capital costs of wind energy.[16] The incremental costs of adding capacity to limited energy plants – increasing the rating of hydro turbines, or the capacity of generating sets for advanced biomass systems for example – may be even less.

The marginal cost of increasing capacity, thus, need not be high and the real long-run value of capacity credit alone is correspondingly low; while it would be an exaggeration to describe capacity concerns as a non-issue their economic importance has certainly been greatly exaggerated. Variable sources are valuable primarily because of their fuel savings and – like all other baseload plants – cannot be justified primarily in terms of capacity needs.

This is a rather theoretical viewpoint and simplifies the interaction between capital and operating costs over time. In practice, the complex and interdependent statistical nature of capacity issues, and the range of options which need to be considered for long-run optimization, is hard to reflect in simplified pricing policies, particularly when utilities buy power produced independently. Utilities generally do not perform detailed statistical analysis and optimization of system reliability, incorporating all the long-run options, in estimating 'capacity payments'. The short-run value of being able to ensure a reliable system is very high, and few utilities attempt to evaluate directly the real capacity contributions from individual variable sources deployed in different regions. Frequently, an inflated capacity value is assigned to producers which can guarantee power at times of peak demand, and none at all is given to sources which fall below a certain threshold of reliability. Such simplifications discriminate against indepedently-managed variable sources.

At higher penetrations variable sources may not save capacity, but they can still reduce capital expenditures in other, perhaps more important ways. By reducing the time for which many thermal plants would operate, they make capital intensive plants (such as nuclear power) less attractive relative to those with low capital cost but higher fuel costs (such as gas turbines). Hence, the optimal plant mix for planning would alter towards lower capital expenditure on other plants. Since changing the thermal capacity mix alters the operating costs, these issues become inseparable from the broader questions of fuel savings. To these we now turn, before returning to a broader overview of the economics of variable power sources at high system penetrations.

Fuel saving: determining factors

The 'ideal' fuel savings from a variable source are those which would be obtained by considering only

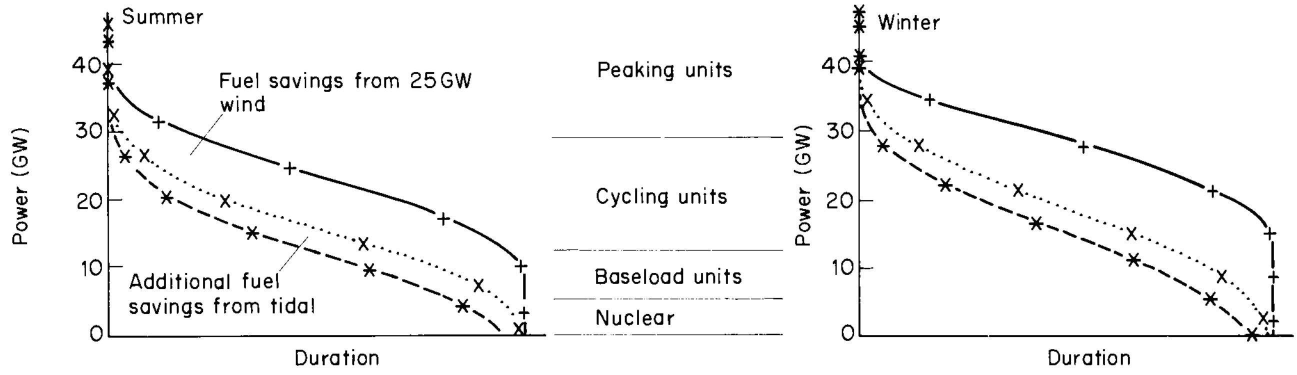

Figure 6. Load duration curve illustration of ideal fuel savings.

Key: + Original load (1971–78 CEGB data).
× Net load after subtracting output of wind capacity used for Figure 1.
* Net load after subtracting output of wind and tidal capacity used for Figure 1.

the reduced operating time required of thermal units after subtracting the variable input from the original demand. The actual fuel savings may differ from the ideal savings due to various operating considerations, as discussed later.

The ideal fuel savings can be estimated from the simple load duration curve representation of the merit order operation of the thermal power system, as illustrated in Figure 1. At low penetrations, the variable input simply 'shaves the edge' off the duration curve. It can then be seen – and proved mathematically[17] – that the fuel savings are not affected by short-term variability and equal that from a perfectly reliable source with the same seasonal pattern of energy output. The extent to which this holds at high penetrations depends upon the detailed characteristics of the output, demand, and thermal plant profile, but again the duration curve gives a useful representation. To illustrate characteristics at very high penetrations, Figure 6 shows the load duration curve corresponding to electricity demand in England and Wales over 1971–78 (a period of relatively constant total demand), and the 'net' load duration curves after subtracting the output from a notional 25GW of wind energy, and from several large tidal schemes as used for Figure 3. The difference between the original curve and the net curves illustrates the ideal fuel savings. Their extent is readily apparent; the available wind energy amounts to around 30% of the total demand and tidal adds another 13% or so.

In this illustration, the peak of the duration curve is not much lower, for there are occasions when demand is high and there is little wind or tidal input. But such occasions are rare so the peak is much sharper and the use of peaking fuels is greatly reduced. At the opposite extreme, the duration curve does go into negative values, reflecting times when the available wind plus tidal power exceeds demand; power would then have to be shed from the wind turbines or tidal schemes. But although the total capacity of variable sources in this illustration greatly exceeds the minimum demand, such occasions are so rare as to be economically almost irrelevant. More significant in this illustration would be the reduced value of savings when the variable input competed with nuclear operation. Nevertheless, if the ideal fuel savings are the only issue to be considered, clearly very large capacities can be usefully accommodated.

There are, however, many complexities to be considered. Operating penalties can be usefully divided into three main components:

- *cycling losses,* due to the increased start-up and shut-down of thermal plants, and other short-term changes in their output;
- *reserve costs,* arising from the need to ensure that the system can respond adequately to unpredicted changes; and,
- *discarded energy,* when the available variable input exceeds the amount which can be safely absorbed while maintaining adequate reserve and dynamic control of the system.

Modern thermal power stations are complex high-precision machines, designed for continuous operation at their rated capacity. It can take many hours, and cost a great deal, to start them up – perhaps £50 000 to start a modern, 1 000 MW coal station from cold, if estimates of associated wear and tear are included.[18] Any power source which greatly increased the need for plant starts would rapidly make itself uneconomic.

However, as emphasized above, variations need

Table 1. Variability coefficients of demand and variable power sources.

Series	Variability coefficient (MW/day/MW mean power)
Electricity demand	0.5
Wind energy (in one major region)	1.8
Wind energy (dispersed over England and Wales)	1.3
Tidal energy (single ebb-generation scheme)[a]	6.3
Wave energy (1 site data – South Uist)[b]	0.8
Solar energy[c]	3.0

Notes: Values estimated from hourly data, except wave (six-hourly data) and solar (estimated on basis of load factor, assuming single daily cycle). [a]Variability of tidal energy might be greatly reduced if several complementary schemes could be combined. [b]Reflects large scheme, with relatively low capacity rating. [c]Solar and load variations tend to be closely related, so that simple comparisons assuming rough independence may be invalid.

to be considered in the context of continually varying demand. As illustrated in Figure 3, dispersed wind energy may vary less rapidly than demand itself. Relative to the mean power, solar energy may vary somewhat more rapidly, and tidal energy more so. In general, cycling costs may be roughly proportional to the 'average variability' of the load on thermal plants in a given period – which is the average rate of change (eg in MW/hour) in the load (in either direction). A rough estimate of the potential impacts can be gained by noting that when variations in the source and demand occur roughly independently, the total resulting variation in the net load to be met by thermal plants is approximately a 'sum-of-squares' addition of the components – in a simplified form:[19]

$$(\text{total variability of load on thermal units})^2 = (\text{total variability of electricity demand})^2 + (\text{total variability of variable source})^2$$

This has several implications. The marginal impact of fluctuations in variable sources at low penetrations is zero – they are lost as noise among demand fluctuations. More generally, the impact can be gauged by comparing the average variability of demand and different variable sources. Table 1 shows the variability coefficient (average variability relative to the mean power) for a number of variable sources in the UK. Dispersed wind energy in England and Wales, for example, has an average variability of around 1.3 GW/day per GW of wind capacity, compared with mean load variation of up to 15 GW/day. Clearly, very large amounts indeed would have to be installed before fluctuations from wind energy became comparable with those already met in the daily demand cycle.

Tidal power appears to be the only source which is likely to incur substantial start-up penalties when deployed on large systems. For the UK's Severn Barrage, which could supply 5–6% of demand with an average 5.5GW cycle every 12.5 hours, this simplified statistical treatment suggests penalties of around 7% of the 'ideal' fuels savings, which accords well with more detailed simulation model estimates of 6–10% performed for government studies of the scheme.[20] Because the diurnal variation of solar energy often parallels that of load, such simplified approaches cannot be used; indeed, solar energy may reduce cycling penalties.

A related concern is that variable sources could increase the maximum rate of change in output required of thermal units. This is primarily an issue of ensuring sufficiently sophisticated system control and the economic penalties involved are likely to be negligible.[21]

The problems arising from the possible unpredictability of variable sources are usually considered to be more significant. In general, 'operating reserve' must be provided to protect the system against such uncertainties. Reserve assessment is complicated because there are many different timescales over which reserve is required, and many different sources of it.[22] They divide into *inherent* reserve, which exist simply because of the nature of the system, and *active* reserve, which must be provided, at a certain cost.

Sources of inherent reserve include: the inertia in the rotating turbines and boiler units; pumped storage and hydro units, which can change their output, and often start-up, very rapidly; gas turbines, which can start up from cold within 5 to 15 minutes; and the running of thermal units above design capacity, which is quite feasible, but increases losses and stresses. Load management and voltage reductions are further options, of increasing severity. Sources of active reserve include: spinning reserve (the spare capacity on thermal units which are running at reduced output); and pre-scheduled or 'banked' plant, ie plant kept on hot standby just in case they are required. Providing such active reserve can incur significant holding costs, in terms of wasted fuel and the reduced efficiency of part load operation for many thermal units. However, in total there is such a wide variety of reserve options that modern power systems rarely fail completely, unless the network itself is severely disrupted.

Two fundamental points govern the impact of unpredictable variable sources on reserve requirements and costs. First, since the variable sources are connected to an integrated system, *operating reserve should be allocated to the system as a whole, not to back up any particular source*. Second, excepting protection against sudden losses (such as the failure of a major plant or single infeed), the costs of *providing* active reserve must be traded off against those of having to *use* one of the various forms of 'inherent' reserve, when the actual prediction error exceeds the active reserve held for that timescale.

In other words, beyond a minimum security level determined by the need for very short-term protection against loss of the largest single infeed to the system, active reserve levels are based on an economic trade-off, not an absolute security requirement – and reserve costs are determined primarily by the average[23] errors involved in predicting the demand upon the thermal part of the system. When errors in predicting the output from variable sources occur independently of those in predicting demand, which is usually a good approximation, the combined error is again a sum-of-squares addition:[24]

$$(\text{average error in predicting net load on thermal units})^2$$
$$= (\text{average error in predicting electricity demand})^2$$
$$+ (\text{average error in predicting variable input})^2$$

Thus again, for small capacities of variable sources, the prediction errors are lost among load fluctuations, with no associated penalty, and models which optimize system reserve levels confirm this.[25] Nevertheless, since demand is fairly predictable, forecasting errors could come to dominate reserve requirements at capacities above 5–10% or so of the thermal capacity if prediction is poor. However, as long as all the energy could be safely absorbed, the economic impact would still be modest, with reserve penalties alone rarely exceeding 5% of the fuel savings.[26]

As the capacity of variable sources increases on a system, various cost penalties may rise other than those considered earlier. Prominent among these is the fact that there might be occasions when the available power cannot be used. This is not simply a matter of the available energy exceeding demand; it would occur well before this stage was reached, because power systems would need to keep a minimum level of thermal plant generating to maintain adequate operating reserve and system control capabilities.

This need not in itself pose any fundamental problems for the integration of variable sources. It is always possible to 'discard' energy by shutting down some of the variable generators, for example by furling the blades on wind turbines. It does, however, result in an economic penalty which becomes increasingly important as the capacity rises further. The 'minimum thermal level' would be determined by many factors, including the predictability of load and variable sources, and the part-load level of the thermal plants. In this context, it is important to note that the ability to part load baseload plants (even nuclear) would be very important at high penetrations of variable sources, a sensitivity brought out by modelling studies.[27]

Such analysis presents a very encouraging picture of the value of variable sources. At small penetrations, their energy is usually as valuable as that from conventional power sources with the same seasonal pattern of output. For applications in which the seasonal variation follows that of demand, the value may thus be greater than that of conventional sources – though this must be compared against the ability to schedule maintenance on conventional sources to follow seasonable load variations, and to maximize availability during peak demand periods. With increasing capacities, the marginal value falls – as capacity credits decline, as the variations and prediction errors become significant in relation to those of the demand, and as occasions when the energy cannot safely be accepted become significant. But overall, it appears that large capacities can be accommodated without major losses.

By way of illustration, the results of modelling studies which attempted to optimize system operation, with the current thermal generating structure but incorporating large capacities of dispersed wind energy in Britain are illustrated in Figure 7.[28] These suggest that over a third of the energy might be obtained from wind energy before the marginal value of the fuel savings declines by over 25%. A study using the same model which also attempted long-term optimization of the plant mix suggested that even higher wind capacities could be economic under some circumstances, resources allowing.[29]

Clearly, such capacities could not be considered for many decades, if ever; the principal conclusion from such results is that system constraints are

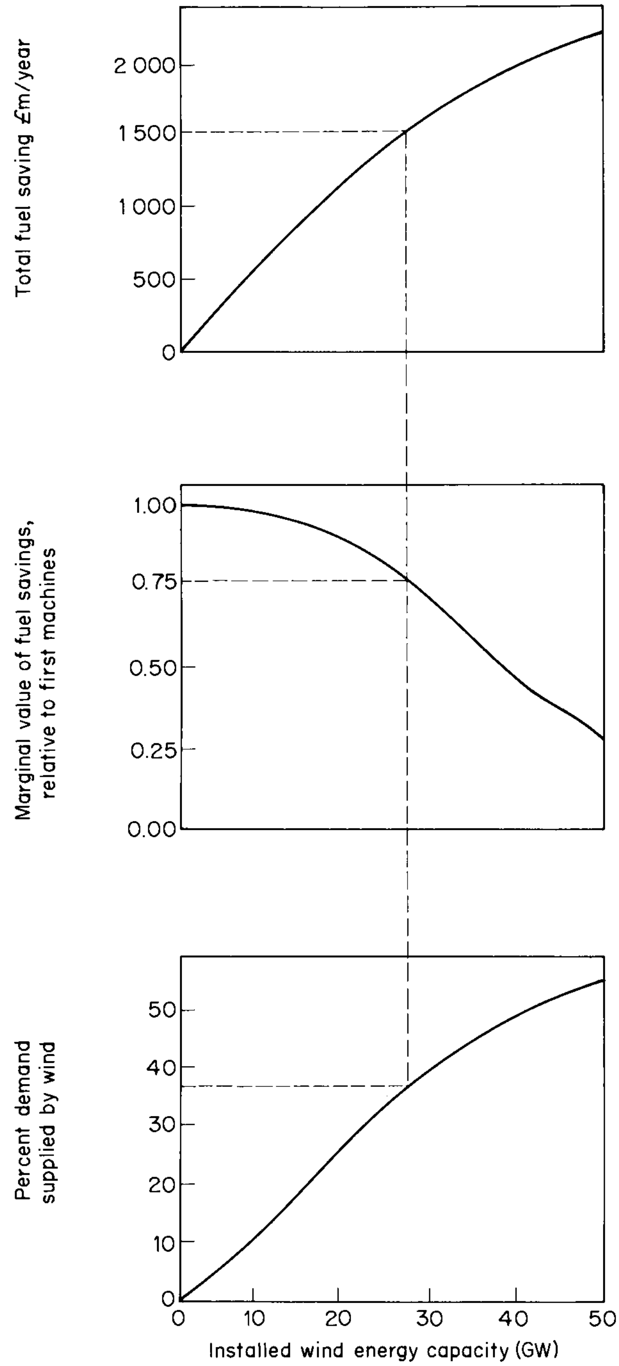

Figure 7. Measures of wind energy fuel savings at increasing penetrations into large power system including operational penalties (thermal capacity is 60GW).

unlikely to be the factor which limits the role of wind energy, at least. Other renewables, and the possible gains from combining them, are considered below.

There are still a range of results and differing views concerning the value of variable sources at high-system penetrations. A broad review and critique of modelling studies has been given elsewhere.[30]

It should also be stressed that results discussed here assume the system operation to be fully integrated, with the various components well coordinated. This may require control procedures to be adapted, and institutionally may not be easy to achieve. For example, Sola and Sioshansi[31] report that variable power has been a 'logistical headache' for the Pacific Gas and Electric utility becaue the input 'does not necessarily match the utility's system requirements.' One reason for this is that the Californian windfarms are all owned by independent power producers, selling output to the grid. The utility has little information on when to expect power and no control over it. Even so, it is not clear that the current experience constitutes any kind of significant economic penalty or security risk to the whole system, but more of an inconvenience for operators, who need to adapt traditional control procedures to the new conditions. There is, however, no doubt that if much more wind energy is deployed in California, the utility will have to have more information and control over night-time power production, and the experience could provide useful experience of the practical issues involved in integrating variable sources.

Interfacing, transmission, and interconnection

The discussion has not so far addressed issues of local connection and transmission. Because most renewable sources generate in much smaller units than conventional power stations, they would be connected at lower voltages (Table 2). To the extent that the power could be used directly on the local low-voltage system, this would reduce transformer and transmission losses as compared with conventional stations, but set against this, voltage fluctuations and other transient phenomena could be propagated throughout the low-voltage network. The engineering requirements for maintaining adequate local quality of supply, fault recovery, etc, is a

Table 2. Connection voltages for given power levels (UK standard voltages).

Power level (MW)	Voltage (kV)
100–700	132
10–50	33
0.5–20	11
0.3–1.0	0.415

Source: 'Integration of renewable energy sources in electrical power systems', *Watt Committee Report on Renewable Energy Sources*, Watt Committee, London, UK, 1990.

subject in itself, and particularly if variable sources use induction generators this will often require additional investment, for example in local capacitors and relays.[32] While these issues are crucial in engineering terms, adequate protection generally adds on a per cent or two to the capital costs of a source like wind energy, and together with the local transmission connection and interface itself is usually considered as part of the overall installation package.

Different transmission and transient stability issues would be raised by very high capacities of variable sources. A strong integrated transmission system would be required to take full advantage of diversity in renewable sources and to allow stable operation with just a few thermal stations connected for providing bulk operating reserve. Such bulk transmission costs are not generally allocated to particular plants, and would depend heavily on the particular circumstances and power flows in question, but obviously in principle they should be accounted for.

Analysis is complicated by innumerable factors. The need for new transmission capacity will depend upon how a new source and line affects the contingency analysis for the system (ie protection against line and plant failure). The costs depend upon whether existing lines can be upgraded, or new lines are required. Traded off against the costs are the benefits arising from reduced losses in lines of greater capacity, and greater flexibility in operating other plant. There can be further complications in relation to variable sources: experience in California, for example, has demonstrated the significance of the wind in cooling transmission lines, so that the effective carrying capacity increases along with the wind power output.

Thorough analysis of transmission issues for general planning applications is probably impossible, but rough estimates can be made. Even in the USA, with relatively low demand density in some regions because of low population density, transmission is typically valued at no more than 10% of generation assets;[33] estimates of the grid assets in England and Wales suggest similar or lower proportions for this (much denser) system. A crude analysis for wind energy suggested that the costs and losses of ensuring adequate transmission would be minor in relation to the benefits of greater wind diversity (including Scotland).[34]

For sources which are much more concentrated in relation to the system, such conclusions may not apply. One such case is probably the Severn Barrage, for which analysis suggests significant grid reinforcement costs. Also, more serious transmission costs and losses would be incurred for tapping renewable sources which are remote from the main demand centres.

The penalties of distance for transmitting electricity increase faster than for fossil energy transport. Large transfers over more than a few hundred kilometres begin to involve considerable costs and (more importantly) dissipative losses, though these are not necessarily prohibitive; there have been serious proposals, for example, for tapping offshore wave energy and Icelandic geothermal electricity via subsea cables to the UK. But bulk transmission over much more than a thousand kilometres appears most unpromising. For these reasons, many have suggested that very long distance transport would involve conversion to hydrogen which would then be pumped through pipes, as discussed in a companion paper by Winter in this series.[35]

Such cases excepted, this discussion suggests that despite the range of possible effects at higher-system penetrations, in most cases the major system constraint on the power which can be usefully accepted from variable sources will be the provision of adequate bulk spinning reserve. This conclusion is reinforced by the inevitably increasing use of automated generation, load and voltage stability controls. If this is correct, assessing the overall value of variable sources becomes amenable to generation modelling analysis up to very high penetrations, suggesting that modelling results such as those summarized earlier, for all their simplifications, do capture the key economic issues.

Combining different renewable sources

As the capacity of any given source increases, its marginal value declines, primarily because successive increments of capacity are correlated with those already on the system. How might different combinations of renewable sources affect the situation?

When sources are directly complementary, there are potential large benefits. Examples of wind and solar energy have been noted earlier with reference to capacity credits; thermally-driven winds may be strongest after sunset, so that the combination usefully covers periods of high demand. In many temperate regions, there may be more general seasonal and short-term complementarity.

Even for sources which are not directly complementary, simple statistical independence makes different variable sources more valuable than just more of the same. An illustration of this was given by studies of wind and tidal sources on the British supply system.[36] One feature which emerged from the investigations was that, when the thermal system was allowed to reach a long-term optimal mix with tidal power, the marginal value of wind energy at low to intermediate penetrations was increased. This initially surprising result occurs because the system adapts to incorporate the tidal power by increasing the ratio of peaking plant to baseload, both because of the changes in the load duration profile and because of the more flexible operational characteristics of the peaking plant. The marginal fuel cost on the system is therefore increased, and it is this which initially determines the value of wind energy. The value of the seasonal match between wind and load is also enhanced by the presence of a source (tidal) which does not vary with the seasons.

In these circumstances the marginal fuel savings from wind decline more rapidly with penetration than in the absence of tidal power. But losses only become serious when the probability of having excess power becomes significant, so that energy needs frequently to be discarded. The fact that wind and tidal are uncorrelated means that this does not occur until high penetrations are reached. The study concluded[37] that 'an integrated British supply system could, if it were considered desirable, absorb at least half of its energy from wind and tidal power combined without significant [operational] difficulties'. Such results reflect the very diverse system (four tidal sites, with unconstrained power flow between England, Wales and Scotland and wind resources in each), but assumed no storage. The transmission requirements would be substantial, though as indicated above, not necessarily prohibitive. Generalization to other systems and other mixes of variable sources is difficult, but it serves to emphasize the fact that very large inputs from variable sources can in principle be accommodated without major losses, without any reliance on storage.

Further possibilities are offered by combining variable sources with energy limited plants, which are usually also renewable and which complement variable sources very effectively. The energy can be used selectively when most required. If the generating capacity can be increased at relatively low cost, it allows greater flexibility in dispatching the energy, reserving it for times with relatively low variable output and high demand. The potential role may be judged schematically from Figure 2, by noting that variable sources will tend to make the demand curve steeper (as in Figure 6), so that a higher energy limited plant capacity can be used profitably to displace similar amounts of peaking fuels, while also contributing more to system reliability.

There are various limits on this. For hydro stations, the ability to increase generating capacity may be distinctly limited by the engineering constraints (eg the physical space available in the dam and/or cavitation on the turbine blades at high flow rates), and by the ecological consequences of greater variation in downstream flow rates. For biomass plants, such problems would not arise, but the incremental costs of increasing generating capacity, and perhaps the storage capacity for dry biomass (which is a relatively bulky fuel), may be rather higher. As yet it is not possible to judge how large the scope will be and, as with many issues surrounding renewable sources, it would vary considerably according to system and resource conditions. But the potential synergisms between different renewable sources are clearly much too important to ignore, and they may often make the combined potential larger than the sum of parts considered in isolation.

Long-term trends and capabilities of supply systems

How might likely long-term developments in power systems affect the integration of variable sources? One of the most significant factors has been identified as the operational flexibility of thermal baseload plants, and in particular the ability to part-load them to provide operating reserve. Most large baseload units, nuclear and thermal, can be run stably down to at least 50% capacity. Below this, a range of problems emerge. To date, there has been little incentive to part-load new baseload plants to any greater degree, because they are intended to run at full capacity; but when it has been required, it has generally proved possible to operate plants down to 30–40% of capacity,[38] and studies suggest that lower levels still could be achieved, at relatively low cost, with suitable modification in design.[39] Minor modifications can also improve responses in terms of the rate of change of output, frequency response etc, but the inertia and sensitivity of highly-tuned steam turbine systems inevitably sets limits on such flexibility.

The current trend towards smaller generating units based on gas turbine technology raises further opportunities. Gas turbines are operationally more flexible and less capital intensive that traditional baseload plants. Both features are favourable to the integration of variable sources. The performance of combined-cycle plants is still partly constrained by that of the steam turbine cycle. But advanced steam-injected gas turbines, based on aero-derivative engines rather than industrial turbines, may offer comparable efficiencies with still greater operational flexibility, including good part-load performance, high load-following capabilities, and even considerable ability to boost power above the design rating with minor penalties in efficiency.[40] As well as being used for natural gas, such technology is probably also the most promising way of exploiting biomass, and perhaps even coal, using gasifiers. The characteristics, combined with the low capital costs, again increase the ease of absorbing high-variable inputs.

The same is probably true for small-scale systems. Steam-injected gas turbines are not only more flexible operationally, they are also practical on much smaller scales than steam turbines, perhaps down to sizes of under 10MW. One intriguing possibility concerns applications on island and other small-scale systems. Such areas at present frequently run on diesel, and the difficulties of integrating variable sources on such systems have been noted. Given the range of fuels which can be used to drive such plants, combinations of gas turbine technology with variable sources could emerge to be a mainstay of decentralized supplies in the future.

Development will not only be confined to the hardware of supply technologies. There is little doubt that for relatively little expenditure, the predictability of most variable sources could be greatly increased, partly through judicious use of existing weather-related data, and partly by developing dedicated monitoring stations (for example, of wind-speed patterns a few tens to hundreds of kilometres from major generation areas) and predictive models. Prediction capabilities would develop alongside any major deployments of variable sources; in reality, unpredictability seems unlikely to be a serious issue.

The discussion has also noted the value of having adequate diversity of the variable source(s). The natural diversity available increases greatly between systems and countries. The existing trend towards greater system interconnection will thus further ease the integration of renewable sources. Spread over Europe, for example, wind energy would be quite a reliable source, and the extent of additional control offered by integrated use of Alpine and Norwegian hydro capacities would add further flexibility.

Finally, whatever kind of system is considered, the growing role of microprocessor controls is likely to be important in both automated generating controls and, more importantly, the short-term management of controllable loads. Industrial load management is already an important feature in many utilities, but the potential of modern technology for increasing the degree to which loads could if desired respond to changing system generating conditions, with benefits to both consumer and producer, has barely been tapped. Development of such techniques is a trend which will again aid the accommodation of variable soures on any scale.

Conclusions

The potential applications of renewable electricity sources are many and varied. The ubiquitous nature of many renewables means that renewable energy is frequently available for small and isolated applications where transporting and using fossil fuels is expensive. In such cases, the penalties and difficulties imposed by the variability of many renewables may be very significant, though they may still be more than offset by the high value of utilizing locally-available resources, even if storage is required to exploit them effectively.

It has been widely asserted that the application of renewable sources on larger power systems will be severely constrained unless cheap storage can be developed. This assertion is without foundation. The discussions in this paper emphasize two main contrary conclusions.

First, when the capacity of a renewable source is small relative to the total capacity of thermal plants – as is currently the case for all renewable sources except (occasionally) hydro – source variability is essentially irrelevant, and the value of renewable energy can indeed be greater than that from conventional thermal sources. This is true for energy limited plants of hydro and biomass because of the greater flexibility in using the available generating capacity, and for variable sources it can be true either due to positive correlations with peak demand (as with solar energy on systems with solar-driven demand peaks) or due to more general seasonal correlations with demand (as for wind and wave energy in temperate zones). In general there is no case for penalizing renewable energy relative to conventional sources at the capacities currently employed or likely over the next couple of decades in most areas.

The marginal value declines as capacities increase, but relatively slowly. In many cases, contributions of perhaps 20% of the demand could be obtained from one type of variable source with only a modest reduction in the value of the energy, and contributions of 30–40% would seem to be feasible before the penalties become severe, even neglecting storage and possible power exchanges with other systems. Various existing trends in power systems will further ease their integration, and by using combinations of different variable sources, storage, and trade between neighbouring systems, there seems nothing technically to prevent large systems developing over periods of decades to accommodate well over half of their power from variable sources.

Given the nature of other constraints, it therefore seems highly unlikely that the use of most renewable sources on large power systems will ever be seriously inhibited by bulk systems limitations. The main possible exception to this conclusion could be the use of PV, where the output can vary quite rapidly and the benefits of resource diversity are least, because the variations are strongly correlated even across entire continents. System constraints on PV could be especially important in densely populated tropical countries which have severely limited biomass resources (due partly to various competing uses), few other renewable resources, and limited access to hydro or gas resources which might ease the integration of such a variable source. Yet even for this, it may be several decades before capacities sufficient to pose serious operational difficulties can be deployed, and other options for easing integration may arise. With this partial *caveat*, it is hard to escape the conclusion that concerns over the integration of renewable sources have been grossly exaggerated. Of all the problems faced by renewable energy, system integration and the supposed penalties of variability seem among the least significant.

[1]Various terms have been applied to sources with fluctuating output, including 'non-dispatchable' and 'intermittent' technologies. 'Variable' is chosen here as the most generally descriptive and distinctive, since some such sources can be dispatched to a limited extent (and thermal sources differ substantially in their practical flexibility) and, taken literally, most sources are 'intermittent' by virtue of mechanical failure if nothing else.
[2]International Energy Agency, *Renewable Sources of Energy*, IEA/OECD, Paris, 1987.
[3]US Department of Energy, *The Potential of Renewable Energy*, SERI/TP-260-3674, Solar Energy Research Institute/DoE, CO, USA, March 1990.
[4]F.R. McLarnon and E.J. Cairns, 'Energy storage', *Annual Review of Energy*, Vol 14, pp 241–71.
[5]T. Flaim, T. Considine, T. Wintholderm and M. Edesses, *Economic Assessments of Intermittent Grid-connected Solar Technologies: A Review of Methods*, Solar Energy Research Institute, Golden, CO, USA, 1981; S. Hock and T. Flaim, 'Wind energy systems for electric utilities: a synthesis of value studies', 3rd annual meeting of the American Solar Energy Society, Minneapolis, MN, USA, 1983.
[6]Since in the area of application (California) these occasions are relatively infrequent, and the dominant capital costs associated with the steam turbine are an integral part of the solar process, the incremental costs of using gas to provide reliable power in this way are small.
[7]R. Hill, 'Review of photovoltaics', in M. Grubb, ed, *Emerging Energy Technologies: Policy Implications and Impacts*, Dartmouth/Gower, Aldershot, UK, forthcoming 1991.
[8]*Ibid.*
[9]J. Ianucci, private communication.
[10]W.M. Somerville, 'Applied wind generation in small isolated electricity systems', in M.B. Anderson and S.J.R. Powles, eds, *Wind Energy Conversion 1986*, MEP Ltd, London, UK, 1986.
[11]N.H. Lipman *et al*, *An Overview of Wind/Diesel R&D Activities*, Rutherford Appleton Laboratory, Oxford, UK, 1989.
[12]J.M. Ogden and R.H. Williams, *Solar Hydrogen – Moving Beyond Fossil Fuels*, World Resources Institute, Washington, USA, 1989, p 63.
[13]See, for example, T.S. Dillon, R.W. Martin and D. Sjelvgren, 'Stochastic optimisation and modelling of large hydrothermal systems for long term regulation', *Electrical Power and Energy Systems*, Vol 2, No 1, January 1980, pp 2–20.
[14]H. Cook, J. Palutikoff, T. Davies, 'The effect of geographical dispersion on the variability of wind energy'; and M.J. Grubb, 'On capacity credits and wind-load correlations in Britain', 10th BWEA Wind Energy Conference, London, UK, March 1988.
[15]J.P. Coelingh, B. van der Ree and A.J. van Wijk, 'The hourly variability in energy production of 1000MW wind power in the Netherlands', Proceedings European Wind Energy Conference, Glasgow, UK, 1989.
[16]The optimal 'backup' capacity would roughly equal the man output in peak load conditions; for wind energy, this is usually 20–40% of the installed capacity.
[17]M.J. Grubb, 'The value of variable sources on power systems', IEE Proceedings C, Vol 138, No 2, March 1991, pp 149–165.
[18]Watt Committee Report in *Renewable Energy Sources*, 'The integration of renewable energy sources in electrical power systems', Watt Committee, London, UK, 1990.
[19]The full derivation is given in M.J. Grubb, 'The integration and analysis of intermittent sources on electricity systems', PhD Thesis, University of Cambridge, 1986, to be published in amended form as a book. A summary derivation and examples are given in Grubb, *op cit*, Ref 17.
[20]*Ibid.*
[21]M.J. Grubb, 'The economic value of wind energy at high power system penetrations: an analysis of models, sensitivities and assumptions', *Wind Engineering*, Vol 12, No 1, 1988, (Section VII).
[22]For a fuller description of reserve options see, *ibid*.
[23]Strictly, the 'average' prediction error in this context is the root of mean square (*RMS*) error in prediction.
[24]Grubb, *op cit*, Ref 17.
[25]See, for example, E. Bossanyi, 'Use of a grid simulation model for long-term analysis of wind energy integration', *Wind Engineering*, Vol 7, No 4, 1983, and associated references.
[26]Grubb, *op cit*, Ref 17.
[27]*Ibid.*
[28]*Ibid.*
[29]M.J. Grubb, 'The potential for wind energy in Britain', *Energy Policy*, Vol 12, No 1, December 1988, pp 595–607.
[30]Grubb, *op cit*, Ref 21.
[31]S.J. Sola and F.P. Sioshansi, 'The role of the US electric utility industry in the commercialization of renewable energy technologies for power generation', *Annual Review of Energy*, Vol 15, 1990, pp 99–119.
[32]G.E. Gardner, 'The supply interface', Proceedings BWEA-Department of Energy Workshop on electrical generation aspects of wind turbine operation, ETSU-N103, Energy Technology Support Unit, Harwell, UK, 1987.
[33]S. Linke and R.E. Schuler, 'Electrical energy transmission technology: the key to bulk power supply policies', *Annual Review of Energy*, Vol 13, 1988, pp 23–45.
[34]Grubb, *op cit*, Ref 19.
[35]Carl-Jochen Winter, 'Solar hydrogen energy trade, *Energy Policy*, Vol 19, No 5, June 1991, pp 494–502.
[36]M.J. Grubb, 'The integrated analysis of intermittent sources on power systems: methods and application', Proceedings IEE Energy Options Conference, Reading, UK, 1987, (Conference Proceedings No 276, IEE, London, 1987).
[37]*Ibid.*
[38]In coping with its over-capacity of nuclear plants, Electricité de France (EdF) developed control facilities to further improve and extend low-load operation, A. Gautier, 'Enhancing PWR flexibility: the reactor advanced manoeuvrability package (RAMP)',

Framatome newsletter, September/October 1984; EdF part-loaded PWR reactors to below 40% of capacity on more than 250 occasions in 1985 (EdF performance statistics 1985). A detailed survey of fossil-fuel plants in the USA found part-load limits varying down to around 30–45%, F.H. Fenton, 'Survey of cyclic load capabilities of fossil-steam generation units', IEEE Transactions PAS-101, No 6, June 1982.

[39]A discussant to Fenton, *ibid*, states that 'many of the existing limitations can be overcome by careful and judicious upgrading and modification of existing equipment, along with the employment of operating procedures designed to improve cycling performance.' The difficulties and costs involved would depend very much on initial plant design.

[40]R.H. Williams and E.D. Larson, 'Expanding roles for gas turbines in power generation', in T.B. Johansson, B. Bodlund and R.H. Williams, eds, *Electricity – Efficient End-Use and New Generation Technologies, and Their Planning Implications*, Lund Univeristy Press, Sweden, 1989.

Appendix 1

The impact of geographical diversity

Exploiting the diversity available between different sites can greatly increase the reliability and predictability of variable sources, and reduce the variations in power output. This Appendix give some quantitative examples, focusing on wind energy.

Wind energy from any one machine would be very variable. A typical wind turbine in temperate zones might be idle for perhaps a third of the time, and could be operating at maximum power for up to another third. At intermediate levels the power output would often fluctuated greatly, even within minutes. The economics of windpower integration depend heavily on having such variations smoothed out between sites.

Some of the potential benefits of diversity within Britain are illustrated in Figure 8, which shows the probability of obtaining different levels of total wind power output (relative to the installed capacity) if wind turbines were sited at many different locations around Britain. In summer, the chance of obtaining maximum power (when some wind energy might have to be discarded) is very small indeed, but there is a 25% chance of output being below 10% of the installed capacity. In winter, such low outputs would occur for only about 10% of the time (or less, if variable-speed turbines capturing more energy from low wind speeds were used), and the chance of obtaining output within 10% of maximum is still barely one in 20. Most of the time, the output would be at intermediate levels.

The effects of diversity on wind fluctuations are just as important. This can be analysed using a 'diversity factor' $D(t)$, which expresses the average variation in output from a group of wind turbines relative to the variations in one machine. This is defined by:

$$\frac{\text{Variation of total output}}{\text{total capacity}} = \frac{\text{variation in single machine} \times D(t)}{\text{machine capacity}}$$

The diversity factor for an array of machines can be found if the 'coherence length' $L(t)$ of fluctuations – a measure of the maximum distance over which fluctuations occur simultaneously – is known. For a square array of N machines spaced a distance d apart, it is given by:

$$D(t) = \tanh(d/2L(t))/(SQRT(N))$$

where $\tanh(x)$ is the hyperbolic tangent $= (e^{x}-e^{-x})/(e^{x}+e^{-x})$.

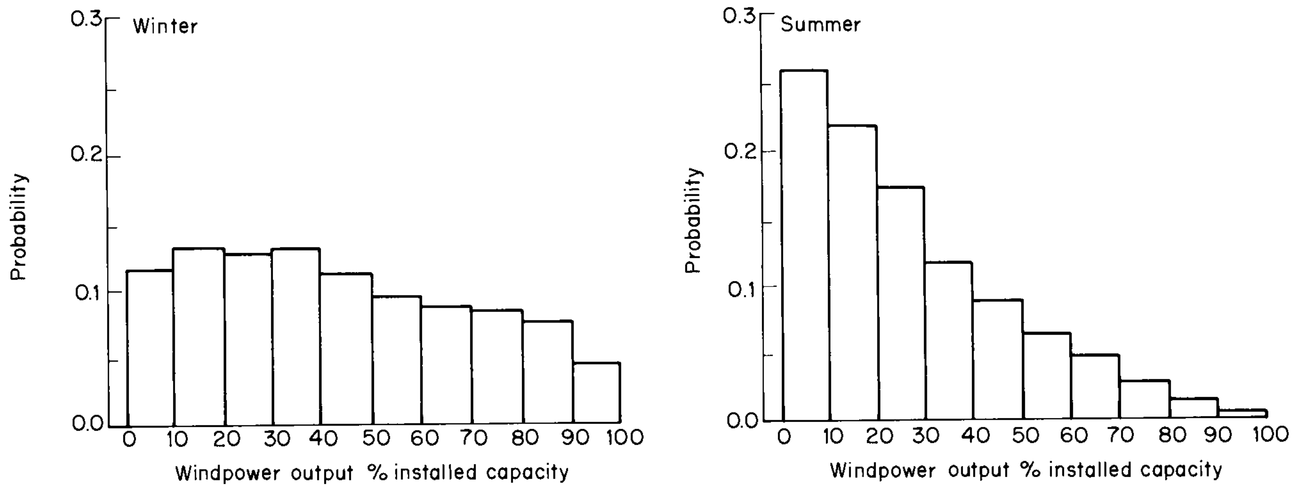

Figure 8. Distribution of output from nationally-distributed wind energy in Britain.

Farmer[41] cites some typical estimates of coherence length associated with various timescales; in practice, $L(t)$ is approximately equal to the windspeed times the timescale t involved. For 'microscale' variations, within tens of seconds, $L(t)$ will be less even than the spacing between machines d. The equation then approximates to $D(t) = SQRT(N)$ – physically, this corresponds to the fact that the fluctuations between the machines are independent. So even if 5 000 wind turbines of 2MW capacity each were deployed in the long term, and the average microscale power fluctuation from each machine was 15% of the capacity, the total variation would be 10 000MW × (15% × 2MW)/2MW × $SQRT$ (5 000), = 20MW. Such fluctuations – about 0.5% of the total wind capacity – would be negligible on large power systems.

When the timescale stretches to 10 minute fluctuations (a timescale of particular interest, since it takes about 10 minutes to start up gas turbines for emergency supply), random fluctuations would only be independent between machines spaced more than about 5–10km apart. In such cases the equations can be applied just as well to evaluate the effects of diversity between clusters of machines. If, for example, the same 5 000 turbines were arranged in 50 separate clusters of 100 machines (many perhaps offshore) the RMS random fluctuations on timescales of 10 minutes to half an hour would be around 150MW – significant, but still small compared with demand variations on most systems which span such an area (eg compared with the 10–15GW diurnal demand cycle in Britain).

This applies to random fluctuations. The effect of storm fronts moving across wind or solar arrays could produce wider correlation. For this, explicit analysis of real data at many sites, together with a detailed stability analysis of the system taking into account the various emergency reserve options available, would be required to conduct a credible 'worst case' analysis. A study of 10 years' data in the Netherlands,[42] a relatively small region compared with the diversity available on many other systems, concluded that on no occasion would the output have declined by more than 40% of the installed wind capacity within an hour, and 'an hourly decrease in wind power output of 30–40% of the installed capacity might occur four times in 10 years.'

Similar conclusions are likely to apply to weather-driven variations in other sources, for example, cloud-induced variations in solar output. Diurnal solar variations, of course, cannot be much reduced by diversity, though the rate of change in the morning and evening may be significantly moderated by a longitudinal spread of several hundred kilometres. Diversity would smooth wave power variations to a degree depending heavily on the locations and orientations relative to the primary wave regime and coast. For tidal energy, although the driving force is primarily lunar, local topography determines the relative timing of tides, so that different sites in the same region can complement each other; the timing and form of output can also vary according to the system design and control.

[41]E.D. Farmer *et al*, 'Economic and operational implications of a complex of wind generators on a power system', IEE Proceedings A, Vol 127, June 1980.
[42]J.P. Coelingh *et al, op cit*, Ref 15.

Appendix 2

Capacity credit from variable power sources

How can variable sources contribute to the reliability of a system when they cannot be relied upon to produce power at times of peak demand? The key logic has been given in the text and it applies equally to all generating plants – none are completely reliable, but a reliable system can be built from them because of the risk of many independent inputs failing simultaneously is so small. Statistically, it emerges that providing a new source fails independently of other units on the system, its contribution to improving system reliability at the margin does not depend on its own reliability – all that matters is the mean energy available at times of system risk. Until their capacity rises above the level of general statistical variation on the system, variable sources thus contribute as much as conventional plants.

This result can be proved in a number of ways. Rockingham proved the result for normally-distributed outputs, and Swift-Hook has given a general proof via binomial expansions.[43] For the less mathematically-minded, a graphical illustration is also possible. Running short of capacity can occur due to any one of thousands of possible combinations of high demand and high plant outage. Figure 9 illustrates the density of failure states $S(x)$ which result in capacity shortfall of x. The total probability of failure is proportional to the area under this line, and the number of potential failures states which will be prevented by adding a new source can be represented as illustrated in Figure 9.

If the capacity of the new sources is small enough, $S(x)$ will be more or less constant over the range of possible plant output, and the contribution to system reliability will be $S(0)$ times the totals source energy output in the period considered – the standard result. The conventional plant capacity can be reduced by an equivalent amount while maintaining the original

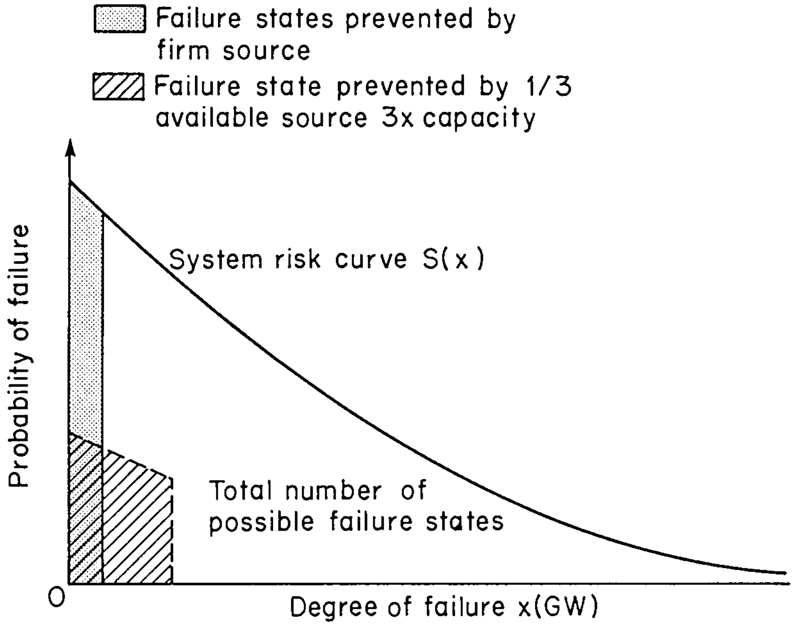

Figure 9. Capacity value of variable source at low system penetration.

level of reliability. This treatment also shows why, and in principle how, the capacity credit will decrease with increasing plant capacity and variability: increasing capacities of a given variable source extend the area of the block to the right, but not upwards, and the reliability contribution from adding more of the same soon declines towards zero if there are significant periods with no output anywhere.

[43]A.P. Rockingham and R.H. Taylor, 'System economic theory for WECS', Proceedings 2nd BWEA Wind Energy Conference, Cranfield, UK; D.T. Swift-Hook, 'Firm power from the wind', Procedings 9th BWEA Wind Energy conference, Edinburgh, UK, 1987.

Chapter 11

Solar Hydrogen Energy Trade

Carl-Jochen Winter

Traditionally, more than 90% (1989) of the world's requirements for primary energy have been met by coal, oil, natural gas and nuclear energy, the rest met by biomass and hydropower. Efficient energy-use is beginning to be viewed as an additional 'energy' and has immense potential, especially in industrialized countries. The possibilities for on-site use of solar energy from irradiance, wind, hydropower, ocean thermal energy gradients, biomass and ambient heat are far from exhausted, despite their growing share of the total. Solar hydrogen will become irreplaceable as an energy carrier because solar energy from areas with the greatest insolation or highest hydropower density has to be seasonally stored and transported worldwide, and in macroeconomically relevant amounts. Solar hydrogen is free of energy raw materials, and thus free of related pollutants. It is also a closed loop energy, compatible with the existing world energy trade system and enhancing it with a product which is inexhaustible, renewable, ecologically responsible and of low-risk.

Keywords: Solar hydrogen energy; World energy trade; Renewable energy

Let us begin with a comparison: in the 1970s and 1980s, German industry supplied pipelines and compressors to Siberia; a bank consortium handled the necessary financing, and in return the USSR provided, year after year, about 30% of the natural gas needs of West Germany. The income from this transaction was used for interest payments and to reimburse the initial capital investment. A quarter of a century later, let's say in 2005, a Canadian–West European contract is signed in which both parties agree to 'construct' a hydropower-hydrogen 'bridge'[1] from Canada to Hamburg. Hydropower plants in northeast Canada generate electricity for the electrolytic splitting of water into its two components, hydrogen and oxygen. The hydrogen is liquefied and shipped to Hamburg on board cryotankers. There it is either cryogenically used as an aerospace or surface transportation fuel, or regasified and added to the natural gas network for sale on the heating market, or electrified in highly efficient fuel cells for sale on the electricity market. Or, another option, solar[2] power plants,[3] located in areas with highest insolation levels, are used to convert solar irradiance into heat and electricity, the latter being used in electrolyzers to split demineralized water, the hydrogen product being transported in gaseous form to the main consumer areas of the world in pipelines, similar to the present treatment of natural gas. If large oceanic distance can make pipeline transport unrealistic, then the hydrogen can be liquefied and transported in cryotankers, as in the Canadian example. More examples could be given.

Are there major differences between the examples of hydrocarbon trade in the late 20th century and solar hydrogen trade in the early 21st century? Common considerations? Advantages, disadvantages? What, specifically? Which positive aspects, which negative ones, require our attention? What are the favourable circumstances, where are the obstacles?

The equivalent of less than 2% of the world's final energy requirements (1986) 500 × 10^9 Nm^3/year (Figure 1) is provided by the present global hydrogen market. In most cases the hydrogen traded is not used as energy but as a chemical feedstock. Theoretically, if all of it were used exclusively as an energy source, it would supply only about half the final energy requirements of West Germany (1986). Thus, the use of hydrogen as an energy source has hardly begun. Only one industrial sector uses hydrogen energetically, space flight, where it is mandatory because of its excellent gravimetric energy density. Only a fraction of the hydrogen currently available is generated using electrolytic processes; most is a product of the steam reforming of methane[4,5], in other words, fossil energy raw mate-

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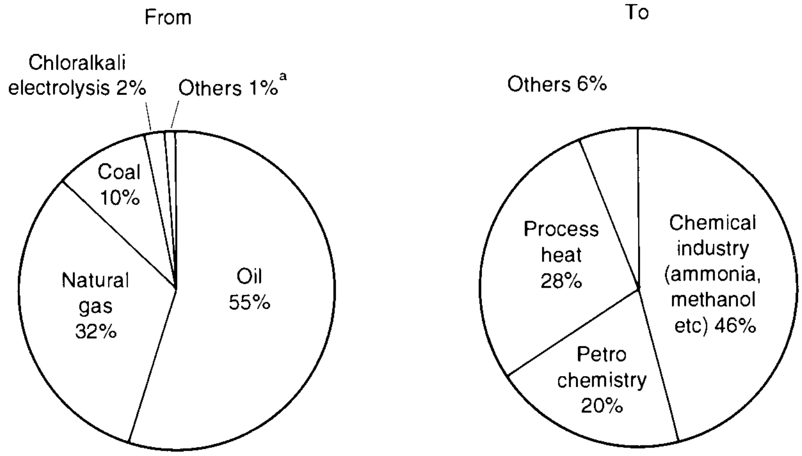


Figure 1. Hydrogen (1986): 500×10^9 Nm^3 approximately 185 mtce/year – about 2% of world end energy consumption.

Note: [a] Water electrolysis < 0.05%.

rials must be utilized for its generation. Thus, at present, hydrogen is not clean, it is fossil hydrogen because hydrocarbons are used in hydrogen energy conversion.

Hydrogen is no stranger: before natural gas, the municipal pipelines which handled the gas supply in West Germany just a few decades ago contained up to 60–70% hydrogen. For the same reason that the shift from town gas to natural gas was carried out in a short time without technical or financial difficulties, it can be expected that the modification back to a mixture of natural gas and hydrogen can be easily handled by a European industrialized country.

The energy of the industrialized world is increasingly being supplied by 'noble' energy carriers in grid networks. Electricity, district heating, and natural gas grids are becoming longer and more closely spaced and interconnected. Energy sources which are not grid-connected, such as coal and oil, will finally become the losers, or they will join the trend to grid networks (oil pipelines, coal slurry pipelines, coal and oil-fired district heating networks, heat/power cogeneration units, coal liquefaction and gasification).

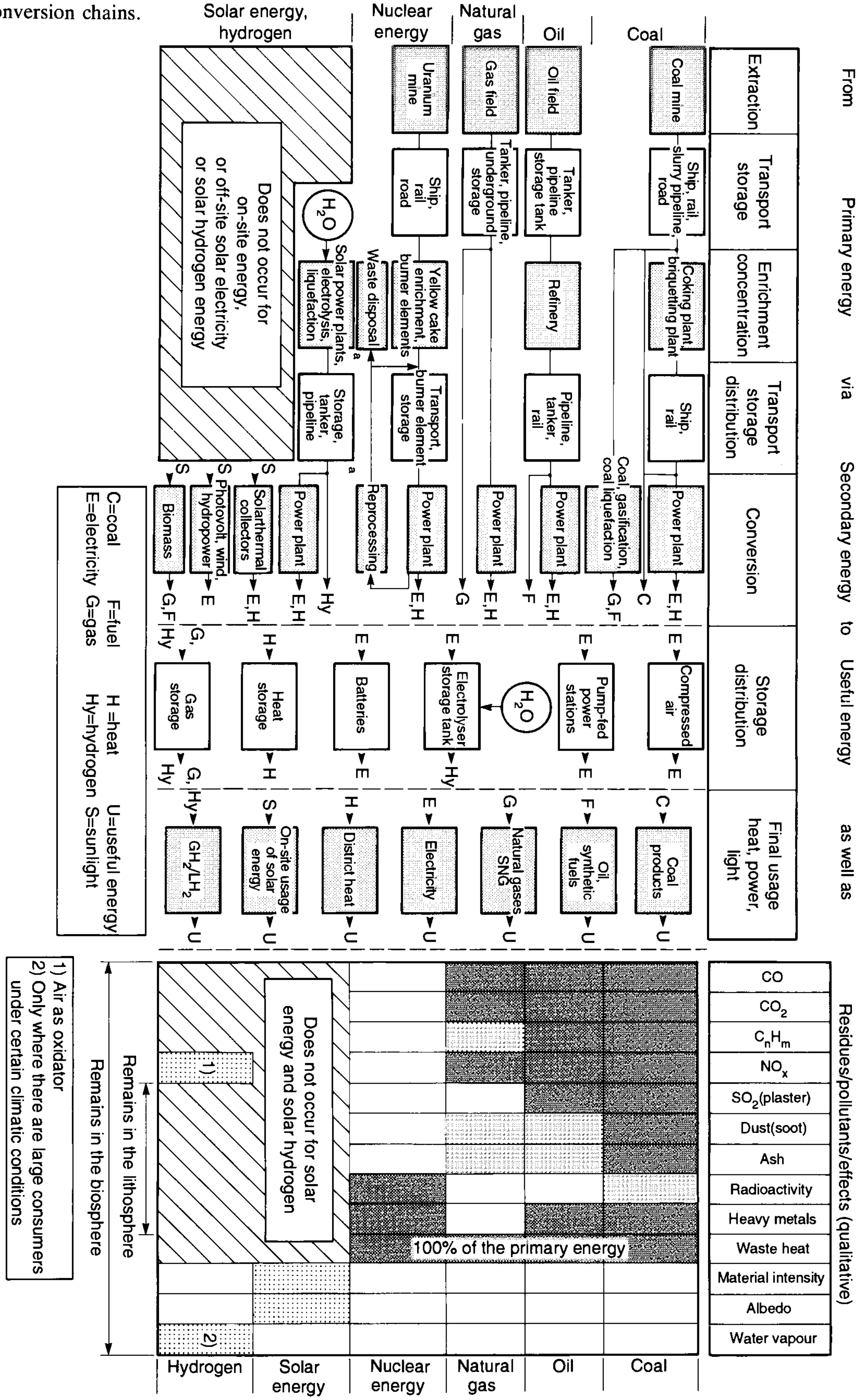
Hydrogen is a noble secondary energy carrier well suited to grid transmission. It is compatible with existing world energy trade and will make use of its immense infrastructure investments and proven reliability. The addition of 10–15% hydrogen to natural gas supplies can be made without significant technical modifications to transportation or calorimetric measuring systems. Only at high pressures above 30 bar are other construction materials (hydrogen embrittlement) and larger pipelilne diameters necessary, since hydrogen has only about one third the volumetric energy density of natural gas. In the Rhine–Ruhr area, a 200 km long hydrogen pipeline has been in operation since the 1930s at above 30 bar, with no reports of serious accidents to date.

Germany imports two thirds of its energy requirements. This situation is not likely to change, even if the country's primary energy requirements, despite economic growth, remain stable or even fall due to industrial structural modifications, strictly pursued energy conservation, and on-site solar energy-use. Hydropower reserves are almost exhausted; lignite strip mining increasingly encounters ecological restrictions, and bituminous coal from the Ruhr and Saar has now to be extracted from mining depths of 1 000 metres and more. Understandably, the cost of domestic bituminous coal exceeds world market prices by a factor of two to four.

In general, the only far-reaching additional energy source available for the medium term is solar energy (irradiance, biomass, wind, hydropower, ambient heat, ocean energy), possibly supplemented by non-solar renewable energies (tidal and geothermal sources). Secondary energy, heat and electricity, cannot be stored on a globally relevant scale and cannot be transported over global distances without considerable losses. Here is where solar hydrogen has a role to play as a secondary energy carrier, making solar energy seasonally storable and globally transportable with low losses. This will guarantee the continuence of world energy trade in fluid energy carriers suitable for grid transmission beyond the time when oil and gas will have to be reserved for hydrogen chemistry.

A global solar hydrogen energy system[6] does not require energy raw materials. Only technology and financing are needed for its installation and opera-

Figure 2. Energy conversion chains.



tion. Its energy conversion chain (Figure 2) does *not* contain, *per se*, two of the three classic energy conversion stages: the energy raw materials stage and the pollutant/waste stage, insofar as it has its source in energy raw materials. Solar energy is in economic terms a 'free good'. It comes from outer space and is returned back to outer space whether people make use of it or not. Water comes from the earth's inventory and returns to it after being split into its components hydrogen and oxygen and subsequently re-combined. The natural, integral loops of energy and matter are not changed by human activity. Even if the world's entire primary energy requirements of about 12 × 10^9 tce/year (1989) were to be met by solar hydrogen – a big 'if' – this would only involve a few thousandths of the total solar energy flux to earth, and likewise only a few thousandths of its atmospheric water vapour content.

However, since no human intervention in nature is entirely without ecological consequences, it is only fair to state that the natural flux of energy and matter would be subjected to geographical dislocations of global dimension (Canada–Europe, Sahara–Europe, Kazakhstan–Europe), and there would be seasonal retardation of the solar energy supply to earth and from earth back to outer space, although both would only be measurable in parts per thousand.

Ecologically, a solar hydrogen energy system is a responsibly clean system as long as the land requirement and energy conversion technologies are environmentally sound, and also because it does not require energy raw materials. It is almost trivial to say that solar hydrogen contains no carbon, no carbon monoxide, carbon dioxide, sulphur and thus no sulphur dioxide, nitrogen oxides, dust, ashes, gypsum or heavy metals. Less than 1% of the otherwise unused arid surfaces of the earth would be needed for meeting the current global primary energy requirements with solar hydrogen using today's available technologies with today's efficiencies and operation and maintenance requirements. Thus, the surface area necessary is not really a limitation. Since solar energy has a relatively low energy density (Central Europe, 100 W/m^2, 1 000 kWh/m^2a; Arabian Peninsula 300 W/m^2, 2 500 kWh/m^2a), a considerable amount of material has to be used to 'concentrate' solar energy up to the densities of fossil energy. Being a natural constant, the insolation level cannot be changed by mankind, but engineers have long been at work to reduce the material requirements, successfully, because paraboloids now weight only 30 kg/m^2 (instead of the earlier 100 kg/m^2) and thin-film photovoltaic cells now only weigh 0.02–0.045 kg/m^2 (monocrystalline cells 2.3–3.7 kg/m^2, whole modules 10–15 kg/m^2). The solar specific investment share for a solar tower power plant (heliostat field, receiver) has dropped from 65–70% down to 35–40% today, thanks to lightweight construction design. Consequently, the conventional investment share (turbines, pipes, valves, heat exchangers and the like) of 60–65% of the total is usual in the power industry.

There has been a fascinating development in energy intensities (see Figure 3). The energy amortization time (how many years an energy conversion system has to be operated in order to produce an amount of energy equivalent to that originally needed for its construction, initial fuel inventory, and its eventual dismantling) is only a few months for fossil and nuclear power plants. But for solar power plants it is a few years, depending on construction design and relative investment costs. This is one side of the coin. The other side shows years in the case of the fossil and nuclear power plants because of the need for a lifetime supply of fuel, and for pollution and waste disposal, whereas for solar power plants it is only a few months, since they of course do not require energy raw materials, and since their potentials for waste and pollutants are zero. If one puts both sides of this coin together and defines the energy gain factor as the result of dividing the electricity generated during the lifetime of the plant by the energy required to erect, maintain and dismantle it, then four statements can be made:

- With energy gain factors of 15–20, wind and hydropower plants are far ahead of the competition, and new developments will put them even further ahead.
- Coal-fired power plants are hardly in the running any more, and they have not even been charged with beginning serious carbon dioxide containment yet.
- Solar power plants have yields that are already close to those of nuclear plants. When nuclear plants are subject to additional safety and security regulations and solar plants are further improved (they are far from reflecting a fully developed technology), then one can expect the gap to become even smaller, and that the solar power plants will finally win the race.
- The above statements are made with respect to a margin of fluctuation which will become smaller as expertise increases.

The solar hydrogen energy system is a closed loop energy system (Figure 4). It can complement the traditional, open fossil and nuclear systems which

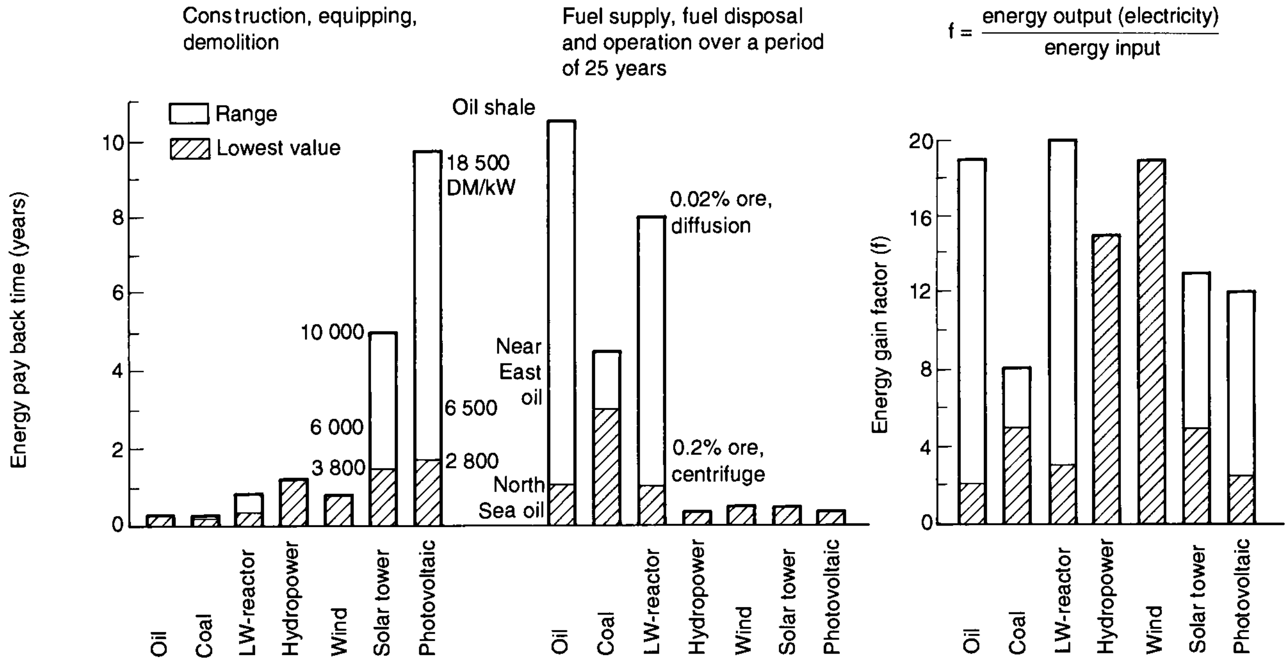


Figure 3. Net energy analysis of power plants.

Sources: Rotty(1975), Moraw(1977), Meyers(1978, 1986), Enger(1979), Sandia(1981), Heinloth(1983), Voigt(1984), Aulich(1986), Hagedorn(1989).

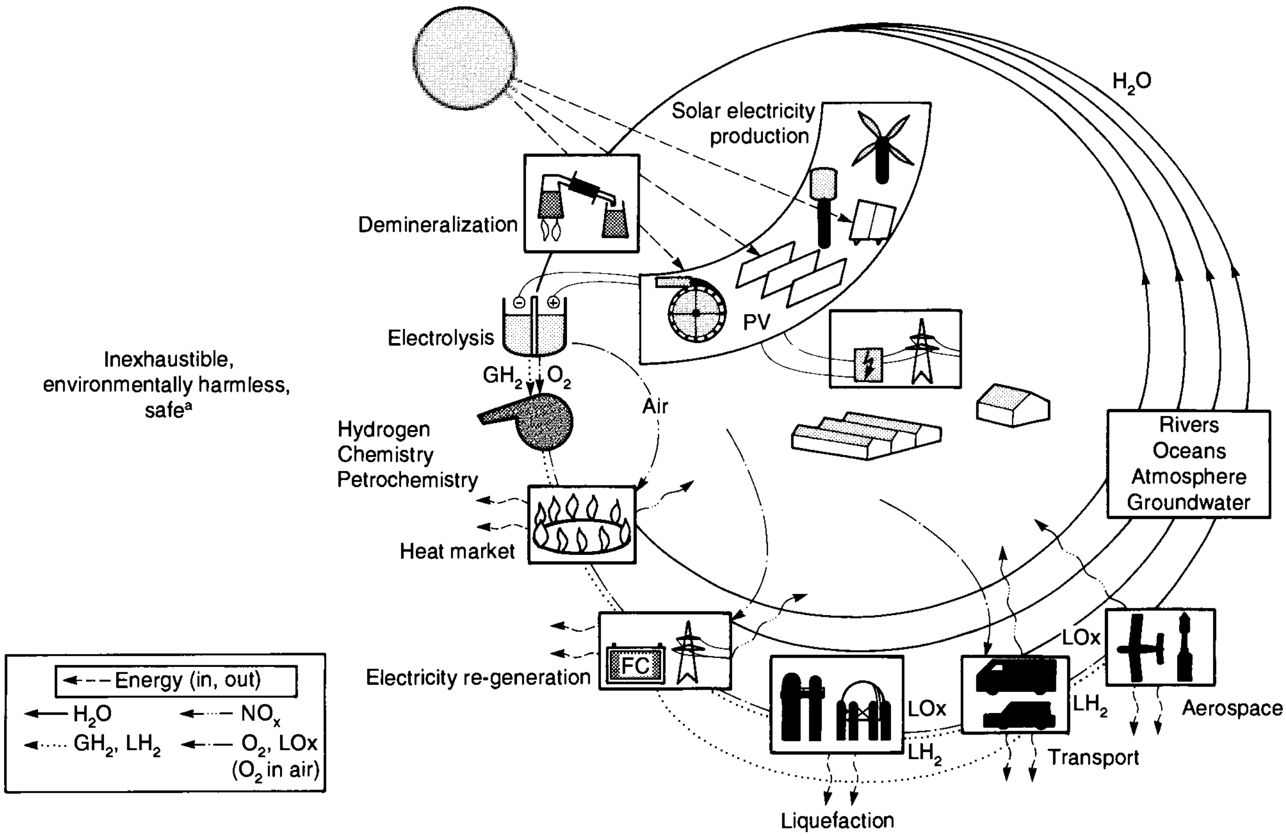


Figure 4. Solar hydrogen: a closed loop energy carrier.

Note: [a] Proper handling presumed.

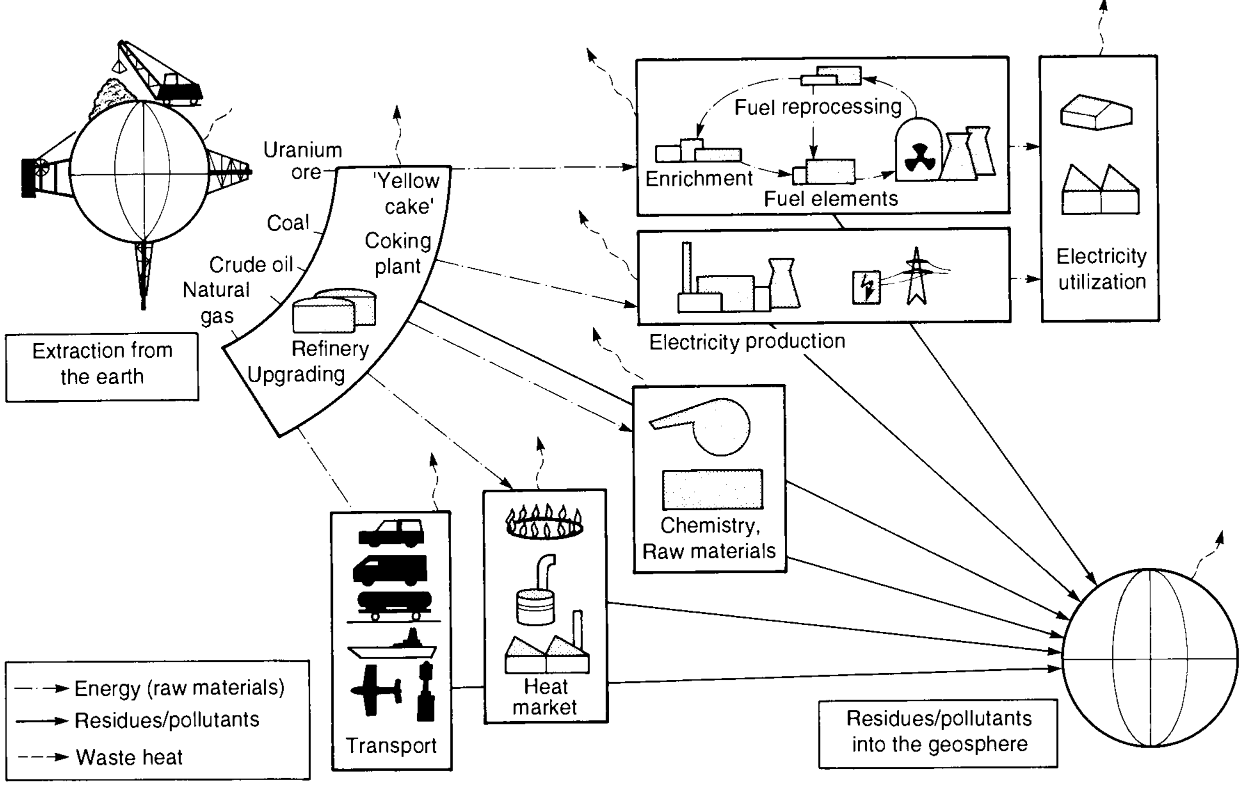


Figure 5. Coal, mineral oil, natural gas, nuclear energy: open ended energy system.

are exhaustible, environmentally harmful and hazardous (Figure 5), and eventually replace them. The traditional energy systems require the removal of energy raw materials from the earth's crust and oxygen from the atmosphere, resources which are – at least regionally – in limited supply. These are then modified chemically or isotopically, and returned somewhere else to the geosphere, sometimes in poisonous form, radioactive in the case of nuclear plants, and associated with CO_2 release to the atmosphere in the case of fossil plants. Both types of plant are responsible for an additive warming of the geosphere equivalent to the total primary energy they consume.

The technologies required for a solar hydrogen energy system are available. They need further development in order to improve efficiencies, service life, mass production, and reduce maintenance, but an abandonment of the approach because of unanticipated problems is very unlikely. In 1989, solar thermal power plants fed 300 MW_e into the grids, and an additional 500 MW_e are under construction or have been contracted. Photovoltaic systems in the order of 40–50 MW_e/year are sold, year after year. Pipelines, electrolyzers, cryotankers, hydrogen storage systems and many other components are state-of-the-art. Fuel cells, hydrogen-filled aircraft and automobiles are being developed.

In a solar hydrogen energy system, constant attention must be paid to safety considerations connected with the global transportation of hydrogen. In comparison to, say, natural gas, it has a wide ignition range and low ignition energy. However, its high diffusivity in air results in a rapid dynamic lift in predominantely a vertical direction, with only limited horizontal spreading. Hydrogen/air hazards are quickly over and there are no long-term liabilities. The absence of any toxicants and radioactivity gives rise to the expectation of high inherent safety. It is a politically responsible system. Its social acceptability will be high, since hydrogen is not really new. However, no technical–energy system is without its own specific safety risks, and these should not be trivilized. For a future solar hydrogen energy system, all the experience which has been gathered over decades, even centuries, in the handling of hydrogen will need to be utilized and further developed. Hydrogen chemisty is 150 years old; there is no nation engaged in space-flight which does not operate hydrogen/oxygen fueled rockets; municipal gas had a high proportion of hydrogen; electric generators are cooled using hydrogen; fats are hardened with hydrogen in the food processing industry and the electronic industry also uses hydrogen. In

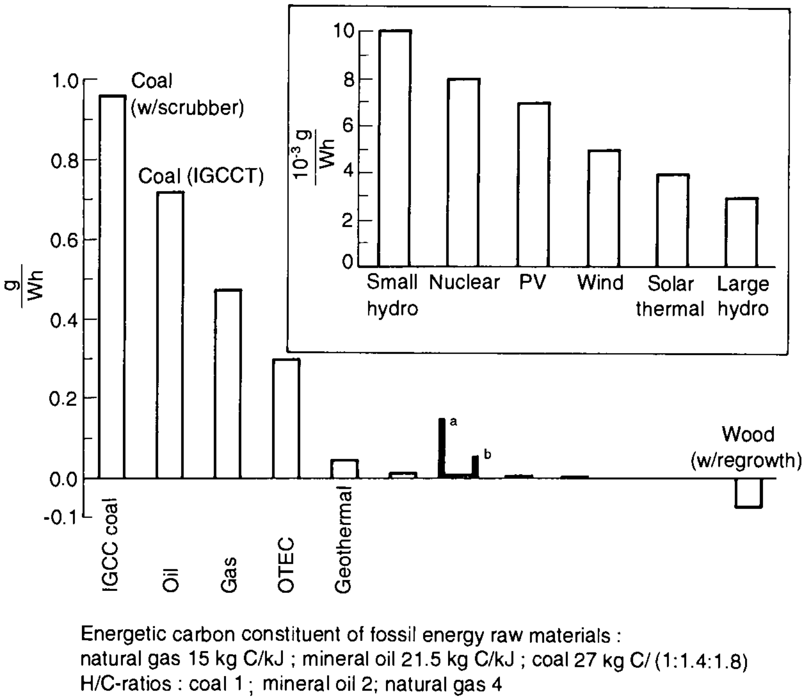


Figure 6. CO_2 emissions in electricity generation.
Sources: Meridian Corp(1989); Worldwatch Paper 91; Öko-Institut(1989).

the USA, France and Germany, among other countries, pipelines have been carrying hydrogen over hundreds of kilometres for decades.

A solar hydrogen energy system would promote international cooperation in energy, in that it is not certain whose dependence is the greater, the customer or the supplier. One can expect stability whenever there is mutual interdependence: a country in the earth's solar belt, or one with enormous hydropower reserves, has, in solar hydrogen energy, a 'national' commodity available for its own energy supply or for export. Such countries require technology and financing from the industrialized countries of the north, which, however, are dependent on the import of solar hydrogen. A wise global policy strives politically for beneficial, balanced interrelationships. Market oligopoly as it exists in the present oil market (and as can be expected in a future global coal market because coal is concentrated in a few supplier countries, Australia, China, North America, South Africa, USSR), is very unlikely in a solar hydrogen market. This is because suppliers exist everywhere on the equatorial belt ± 30–40° N/S, complemented by places with high hydropower reserves (Africa, Asia, Canada, Greenland, South America).

A solar hydrogen energy system will not come cheaply. The well-established infrastructure of the present world energy trade system, which represents an immense investment, should be further utilized wherever possible. A solar hydrogen system has two financial advantages over the fossil and nuclear systems:

- Almost all of the investment is made right at the beginning when the technology is installed. There is no subsequent dependence on energy raw materials and their price fluctuations. Installation times are short (for example: under 12 months for a 80 MW_e solar thermal power plant); risks are low.
- The external costs are very low. By comparison, fossil power plants have yet to contain the CO_2 they produce, and nowhere in the world has the problem been solved of how to achieve the politically responsible, safe, final, realistically large-scale disposal of radioactive fission products and end-of-life nuclear fuel elements. The associated increases in the cost of fossil and nuclear energy will encourage the adoption of solar hydrogen. Figure 6 shows that non-fossil energy converters emit only 1% or less of the CO_2 emitted by fossil fuels. (They do emit some, because steel mills, glass factories and cement works have to be operated to produce solar, wind and hydropower plants!) Throughout the world research and development is going on in solar hydrogen energy

- Experts' report on The Solar Hydrogen Energy Economy submitted to the Federal Ministry of Research and Technology (1988)
- Solar and Hydrogen Energy Research Centre Baden-Württemberg, a foundation, established (1988)
- Future Energies Forum, (including hydrogen), Bonn, established (1989)
- Solar and hydrogen budget increases in national laboratories (DLR-German Aerospace Research Establishment, Jülich Research Centre, Hahn-Meitner Institute, Fraunhofer Society) approved (1989)
- 350 kW_e German-Saudi HYSOLAR project in operation in Saudi Arabia (1990) phase 1, phase 1b approved, phase 2 under negotiation
- 500kW_e Solar Wasserstoff Bayern in operation in Germany (1990)
- 70MW_{th} H_2 / O_2 Spinning Reserve Plant, study phase II completed, 2 plants to be erected
- 100 MW_e Euro-Canadian Hydropower-Hydrogen 'Bridge', study phase I completed, phase II under way
- Society for the introduction of Hydrogen into the Energy Economy, Hamburg, founded (1989)
- World Hydrogen Energy Conference #11 1996 in Stuttgart endorsed

Figure 7. West Germany: status of hydrogen energy activities (1990).

technology.[7] Figure 7 lists hydrogen energy activities in Germany of recent years.

Without doubt, mankind is being confronted with developments in energy policy and related industry policy which are as far reaching as those at the close of the 18th century when the large-scale use of coal opened the path to industrialization. The possible doubling of the earth's human population within a few decades, the increasing scarcity and oligopolization of oil, and the anthropogenic attack on the world's ecological system will mandate a reform of the energy supply system. It will have to use ever fewer energy raw materials, which means that it will become more technologically and financially intensive, and it will have to become a closed loop: hydrogen and solar energy fulfill these demands to a high degree. They are, in terms of human measuring scales, inexhaustible, renewable, of low risk, and ecologically responsible.

Renewable solar hydrogen energy: great hope or false promise? It is, of course, a great hope, but more compelling, a necessity and a growing reality. To traditional energy sources which dominate the

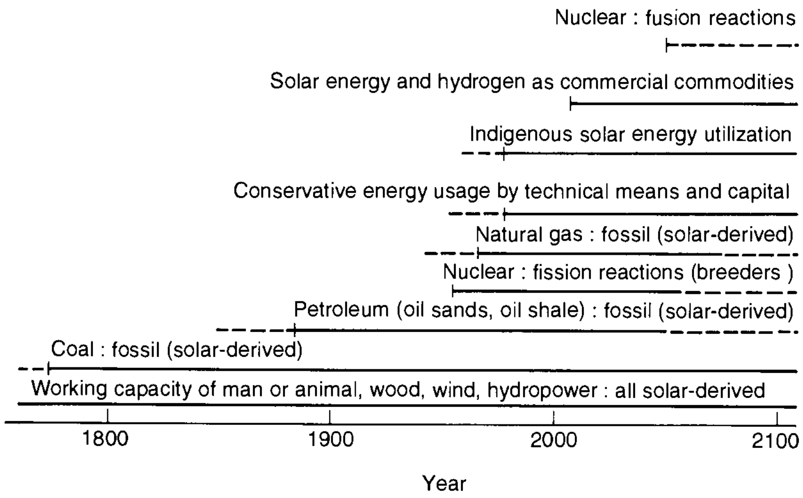


Figure 8. History of the world energy economy (qualitative).

world's present energy system, coal, oil, natural gas and nuclear, must be added energy efficiency, on-site solar energy utilization, and solar hydrogen energy (Figure 8).

Hildegard Euler-Hutflesz typed the German manuscript, Susan Giegerich translated it into English and arranged for the figures, bibliography and final editing – sincere thanks to both of them.

[1]J. Gretz, 'The 100 MW Euro–Quebec hydro-hydrogen pilot project', in *Wasserstoff-Energietechnik*, II, VDI-Berichte 602 und 725, VDI-Verlag Düsseldorf, 1989.
[2]Solar energy in the context of this paper comprises all direct or indirect energies depending on the sun's irradiation onto the earth's surface: passive or active utilization of radiation, biomass, wind or hydropower, ambient heat, oceanic enthalpy differences etc.
[3]C.-J. Winter, R. Sizmann and L. Vant-Hull, *Solar Power Plants*, Springer, Berlin, Heidelberg, New York, in preparation.
[4]*Op cit*, Ref 3, I and II, 1987 and 1989.
[5]D. Behrens, 'Wasserstoffwirtschaft – Herausforderung für das Chemieingenieurwesen', Vorträge Vom 23, Tutzing-Symposium der DECHEMA, Vom 10, bis 13, März 1986, in DECHEMA Monographien Vol 106, Frankfurt am Main, Germany.
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Part III: Renewables and Development

Chapter 12

Biomass Energy

– lessons from case studies in developing countries

D.O. Hall, F. Rosillo-Calle and P. de Groot

Biomass is the world's fourth largest energy source and the first in developing countries representing 14% and 35%, respectively, of primary energy. The provision and use of biomass energy is a complex issue; it is an integral part of the problems associated with sustainability of all types of vegetation which in turn is a key to ensuring stable socioeconomic development. The financial costs of producing biomass are also very complex since they depend upon many different factors and tend to be quite site specific, eg agricultural and forestry costs, type of feedstock and its productivity, equipment requirements, etc. The last two decades have witnessed numerous proclamations of failure and success of biomass schemes. There is no short cut to trying to understand the factors required for success except by extensive investigation. We consider the socioeconomic and technological implications of four case studies where we have had long-term direct experience of evaluation at the local, national and international levels. These case studies are: ethanol from sugarcane in Brazil and Zimbabwe; community biogas in an Indian village; and, land rehabilitation for fuel and fodder in Baringo, Kenya.

Keywords: Biomass; Renewable energy; Developing countries

Since the recognition of the importance of biomass energy in the early 1970s, there have been many schemes and projects to help improve the supply and use of biomass in both developing and developed countries. Considerable efforts have been made to use wastes and residues and other sources of biomass such as sugarcane, short rotation forestry, etc; these would provide solid, liquid and gaseous fuels to rural and urban dwellers, to agriculture and industry and transport.

Biomass currently provides about 14% of the world's energy, equivalent to 25 million barrels of oil per day. It is the most important source of energy in the developing world (35% of total energy) where three-quarters of the world's people now live and 90% of the world population will live by the middle of the next century. Biomass also plays a significant role in a number of industrialized countries, eg the USA and Sweden, which obtain about 4% and 13% of their energy, respectively, from biomass.

Over the last 20 years there have been numerous proclamations of failure and success of biomass schemes and projects. Much of the criticism has been warranted and has certainly helped focus attention on such projects' shortcomings and often uncritical acceptance. The present designation of a 'successful' project must be seen as relative to past failures and not imply that all components of a project are acceptable for any specific programme. Ideally a successful biomass programme should show sustainability, replicability and flexibility and also be economic when all costs and benefits are considered, especially externalities.

There is in reality no short cut to trying to understand the successes and failures of projects except by prolonged and repeated local visits and discussions over an extended period. This also requires interaction with diverse groups associated with a project.

From our experiences and biases with biomass projects, the importance of early involvement by and benefits to the local people, the need for flexible aims, a policy of monitoring research, a long-term approach, and multiple benefits, all stand out as being essential to success.[1]

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In this paper we examine four biomass projects which are 'successful' to different degrees: ethanol production from sugarcane in Brazil and Zimbabwe; community biogas in an Indian village; and, land rehabilitation for fuel and fodder in Kenya. The Brazilian case demonstrates the need for a clear government commitment, the vulnerability of such programmes to short-term market fluctuations and the inherent difficulty of long-term energy planning. In Zimbabwe the State played a largely regulatory role to create acceptable market conditions for the ethanol project to succeed, leaving the funding entirely to the private sector. The biogas project in India and land reclamation in Kenya highlight the importance of social factors and long-term commitment in successful energy and development projects.

Economics and policy

Biomass energy is often considered problematic because it has many facets and interacts with so many different areas of interest such as land use, forestry, agriculture, animals, and societal factors. The provision and use of biomass energy is a complex issue and is only one part of the problems associated with sustainability of all types of vegetation, which in turn is an integral part of ensuring stable socioeconomic development. Biomass energy should not only be considered as an 'energy source' but also as a reflection of the way in which many traditional (and some modern) societies produce, distribute and consume various biomass resources including energy. Biomass projects to enhance energy availability are also very difficult to quantify because of the many 'intangibles' involved.

The cost of producing biomass energy depends upon many different factors such as agricultural and forestry costs, the type of raw material utilized, the location of the manufacturing plant, the design, type and degree of modernization of equipment required in production and conversion, the relative labour costs, the scale of production, and the total investment. There is no such thing as 'fixed biomass energy production costs' since they usually vary according to local conditions. The economics of biomass are, therefore, quite site specific especially if one excludes the conversion and process technologies which by themselves are a relatively small percentage of the overall costs. The provision of biomass energy on an economic basis undoubtedly needs local entrepreneurs to make judgements and decisions.

The following four examples are taken from a large study of 22 biomass energy projects in 12 developing countries which should not be construed as representing all the possible data which is available. The criteria for selection of these 22 projects were that as much economic data as possible was available in a disaggregated form and/or the projects had been operating for some years (the longer the better). There are in fact very few operating projects which fulfil both these requirements. Indeed the only operating technologies in specific cases which allow reasonably extensive analyses are ethanol, energy plantations, charcoal, biogas, and possibly gasification in developing countries, and in developed countries some programmes for producing ethanol, electricity from wastes and residues, short rotation forestry, and possibly biogas. In the following four case studies the authors have had long term direct experience of evaluation at local, national and international levels.

Hall[2] distinguishes three main biomass-related technological categories each of which can be associated with different economies: 1) operating technologies which allow reasonably extensive analysis eg ethanol and charcoal; 2) technologies which are at the 'take off' stage eg biogas, stoves and gasification; and c) projects to rehabilitate degraded land areas or to provide biomass in its various forms to local people eg social forestry and agroforestry.

Ethanol from sugarcane falls into the first category of technologies which are presently commercial; biogas production has been underway for many years and can be considered within the 'take-off' category; and the Kenyan land rehabilitation project within the third category of projects which are very difficult to analyse economically, and can hardly be considered to be economically viable when evaluated by conventional criteria (even though they may have been operating for many years). Each of these categories present their own problems, difficulties and opportunities and each can be associated with different levels of economic evaluation.

Within the first category, which includes ethanol, the technologies are often universally available so that technology transfer to optimize production and conversion can be quite easy. Indeed, a number of developing countries could adapt and improve the technologies for these so-called modern biofuels, eg efficient ethanol distillation plants with low output of effluents, and biomass gasifiers plus turbines for electricity. The main contentious problems are with economics. However, if 'externalities' such as employment, import substitution, energy security, environment, and so on, are also considered then the economics change usually in favour of the biomass systems.

Table 1. Brazilian sugarcane, sugar, and alcohol production and percentage of alcohol-fuelled cars, 1976/77–1988/89.

Year	Sugar cane (Mt)	Sugar (Mt)	Ethanol (10^9l)	Alcohol cars (%)
1976/77	88	7.2	0.6	–
1977/78	105	8.3	1.5	–
1978/79	108	7.3	2.5	0.3
1979/80	118	6.6	3.4	28.5
1980/81	132	8.1	3.7	28.7
1981/82	133	7.9	4.2	38.1
1982/83	167	8.8	5.8	88.5
1983/84	198	9.1	7.9	94.6
1984/85	211	8.8	9.2	96.0
1985/86	224	7.8	11.8	92.1
1986/87	217	8.1	10.5	94.5
1987/88	224	8.0	11.5	84.4
1988/89	241	8.0	12.3	70.0[a]
1990	–	–	–	50.0[a]

Notes: The years correspond to calendar years from 1979 through 1990; [a]means estimated. Column 4: % of alcohol cars manufactured in year.
Source: Compiled from, Mazzone, *op cit*, Ref 5.

In the second category there begin to be opportunities for entrepreneurs to operate and for costs to decline in relation to technical improvements. Biogas digesters can be constructed with designs for lower cost and easier maintenance and an infrastructure for technicians and builders established. Such technologies still usually require some form of subsidies and/or aid but the social costs and benefits are much more clearly seen compared to category three. The policy and institutional changes required for wider dissemination are also more clearly discerned and thus decisions are more easily taken and maintained.

The most complex situation is with the third category where socioeconomic and land use problems are diffuse while also being of overriding importance. Long-term funding is essential both to allow sustainable techniques and technologies to be developed, and to encourage replicability. Conventional economic paybacks are usually very tenuous so making it difficult to progress to the second category where economic criteria become much more important.

The options for producing and using biomass as a source of energy are numerous. The problems of provision and use generally lie in the ability to have good productivities on a sustainable basis to provide energy and other benefits which are desirable from economic, social and environmental viewpoints. Generalizations are difficult and can only be derived from individual case studies which have been carefully analysed over long-time periods.

Brazil case study: ethanol from sugarcane

Global interest in ethanol fuels has increased considerably over the last decade despite the fall in oil prices after 1981. A number of countries have pioneered both large and small-scale ethanol fuel programmes. Worldwide, fermentation capacity for fuel ethanol has increased eightfold since 1977 to about 20 billion litres per year in 1989. Ethanol fuel is produced on a large scale in Brazil and the USA.[3] The current USA fuel ethanol production capacity is over 4.6 billion litres and there are plans to increase this capacity by more than 2.3 billion litres. However, doubts remain as to the future direction of this industry due to the controversy regarding costs. Highly variable maize and by-product prices and the wide variations in final ethanol costs among existing plants over time highlight the non-subsidy aspects of the costs controversy in the USA.[4]

Brazil has the world's largest bioethanol programme. Since the creation of the National Alcohol Programme (ProAlcool) in 1975, Brazil has produced over 90 billion litres of ethanol from sugarcane. In 1989, over 12 billion litres of ethanol replaced almost 200 000 barrels of imported oil a day and almost four million automobiles now run on pure bioethanol and a further 9 million run on a 20 to 22% blend of alcohol and gasoline. Table 1 shows sugarcane, sugar, and alcohol production as well as sales of alcohol-powered cars. Sugarcane production has increased from about 88 Mt in the 1976/77 harvest to 241 Mt in 1988/89, while alcohol production has increased from about 660 million litres to 12.3 billion litres during the same period; in 1985, 96% of all newly-sold cars were fuelled by ethanol, but was down to an estimated 50% in 1990 due to difficulties in alcohol supply and retail prices.[5]

Although Brazil's involvement with alcohol fuel dates back to early this century, the creation of the ProAlcool in 1975 represented a fundamental political step in the country's long-term commitment to provide a substitute for imported oil. The programme has been an outstanding technical success, its physical targets were achieved on time and its costs were below initial estimates. It was an ambitious and creative attempt to deal with the consequences of long-term increases in oil prices that was widely anticipated in the 1970s and the problems of energy scarcity. ProAlcool was planned centrally but it has been executed by private industry in a decentralized manner.

The ProAlcool objectives went far beyond energy alone. It involved an intricate and politically difficult combination of economic policy in the agricultural and industrial sectors with incentives for smaller scale production, public investment in agricultural research and, especially in the northeast of the country, incentives for private innovation and investment. The decentralized execution of such a programme depended on an effective integration of economic and technology policy.

ProAlcool was thus set up with multiple purposes although the main objective was to reduce oil imports. The broad objectives can be summarized as follows: to lessen the country's external vulnerability to oil supply and to reduce oil imports for the automobile and chemical industries; to increase the utilization of domestic renewable energy resources; to develop the alcohol capital goods sector and process technology for the production and utilization of industrial alcohols; and, to achieve greater socioeconomic and regional equality through the expansion of cultivable lands for alcohol production and generation of employment.

To ensure the success of the programme the government established a series of norms. These included: direct involvement by the private sector; economic and financial incentives to ethanol producers; guarantees to purchase ethanol production within the authorized limits and specifications established in advance by the government; establishment of a price policy to ensure an effective remuneration to alcohol producers; and, incentives for alcohol production and utilization technology. The combination of these factors, together with the introduction of new equipment, increases in productivity and the number of new plantations, has given a continued boost to alcohol production during the 14-year life of the ProAlcool programme. ProAlcool has been largely successful in meeting its technological objectives, reducing oil imports and some broad development goals. It has enabled the sugar and alcohol industries to develop their own technological expertise along with greatly increased capacity.

Technological improvements have resulted in sugarcane productivity increases in the agro-industrial sector of 4.3%/year during the period 1977/78 to 1985/86 and a sharp reduction in costs. For example alcohol productivity has increased from 2 660 litres/ha in the 1977/1978 harvest to 3 800 litres/ha in 1985/86.[6] Cane productivity has also increased from 39 t/ha in 1940 to 42.5 t/ha in 1960, 49.3 t/ha in 1976, 57 t/ha in 1980 and 62.6 t/ha in 1988.[7]

New varieties of sugarcane have been developed in order to gain greater productivity on poor soils, in consideration of the need to expand sugarcane growth without interfering with traditional food production. Intercropping and rotation cropping technologies developed by the Brazilian sugar research laboratories have also made it possible for sugar plantations to increase food production. The Brazilian government has undertaken a major effort to promote the improvement of cane production technology, eg the establishment of cane prices based on sucrose content rather than on weight, efficient management of sugarcane plantations, pest control, etc.

Brazilian firms have also been exporting alcohol technology to developing countries and even to some industrial countries. The sugar and alcohol industry is today among Brazil's largest industrial sectors. In short, ProAlcool has stimulated the building and improvement of a modern and efficient agribusiness capable of competing with any of its counterparts abroad. In fact so successful were Brazilian distillery manufacturers in producing efficient hardware that when contracting with international companies for the Brazilian market, the distilleries frequently were found to perform at up to 20% or 30% above their rated capacity. In a number of distilleries, small additional investments have increased production still further to 50% above nominal capacity.[8]

Another industry which has expanded greatly due to the creation of ProAlcool is the ethanol chemistry sector. A significant expansion stimulated by ProAlcool was able to draw upon a tradition dating back to the 1920s. Installed capacity for ethanol utilization in the chemical industry rose from 60 105 t in 1976 to 336 980 t in 1984. From 1975 to 1985 the ethanol-based chemical sector consumed a total of nearly 2.2 billion litres of ethanol i.e. about 3.5% of the annual alcohol production.[9]

Although in recent years interest in ethanol chemistry has somewhat subsided due to the fall in world oil prices, Brazil has had an excellent opportunity to develop this industry thanks to the combination of a sound technological base and historical experience, abundant raw material (ethanol) with a considerable scope for cost reduction, and a large potential market. Ethanol-based chemical plants are more suitable for many developing countries than petrochemical plants because they are smaller scale, require less investment, can be set up in agricultural areas and use raw materials which can be produced locally.

In the ProAlcool programme technological developments have not always matched the stated social objectives. To expect so would be to ignore Brazil's social, economic and political realities. Until recently the government's chief objectives have been economic growth, with relatively little emphasis on social development and, in the specific case of ProAlcool, to achieve greater energy independence and to prevent the collapse of the sugar industry. Economic development has taken place at the expense of social development. Rural job creation has been credited as a major benefit of ProAlcool because alcohol production in Brazil is highly labour-intensive; thus some 700 000 direct jobs with perhaps three to four times this number of indirect jobs have been created. How many of these jobs are new ones is still contested, however.

Environmental pollution by the ProAlcool programme has been a cause of serious concern, particularly in the early days of the programme. The environmental impact of alcohol production can be considerable because large amounts of stillage are produced and often escape into the waterways. For each litre of ethanol the distilleries produce an affluent of 10 to 14 litres of high biochemical oxygen demand (BOD) stillage. However, in the later stages of the programme serious efforts were made to overcome these environmental problems and today a number of alternative technological solutions are available or being developed. This has sharply reduced the level of pollution, eg decreasing effluent volume using Biostil process and turning stillage into fertilizer, animal feed, biogas, etc. This together with tougher environmental enforcement has reduced pollution considerably.

Costs

Despite many studies which have been done on nearly all aspects of the programme, there is still considerable disagreement with regard to the economics of ethanol production in Brazil; this is because there are so many tangible and intangible factors to be taken into consideration. Such a detailed analysis is beyond the scope of this paper.[10]

Both the economics of the production cost of ethanol and its economic value to the consumer and to the country depend on many factors. For example, production costs depend on the location and management of the installation, and on whether the facility is an autonomous distillery in a cane plantation dedicated to alcohol production, or a distillery annexed to a plantation primarily engaged in sugar production for export. The economic value of ethanol produced, on the other hand, depends primarily on the world price of crude oil and then on whether the ethanol is used in anhydrous form for blending with gasoline, or in hydrous form in 100% alcohol-powered cars.

The current relatively low oil prices (about $19–20/bbl, mid-1991) together with increased domestic oil production has decreased the overriding importance of alcohol as a liquid fuel substitute although supply interruptions and energy security are still of great concern to Brazil. This is further reinforced by the economics of alcohol production which, despite considerable improvements, still remain unfavourable compared to oil prices on a microeconomic basis.

Cost estimates of ethanol production in Brazil can vary significantly. Reddy and Goldemberg[11] estimate that the average cost of ethanol produced in Sao Paulo State in 1990 was about $0.185 per litre; at this price, ethanol could compete successfully with imported oil. Ethanol production costs have fallen 4% per year since the late 1970s due to major efforts to improve the productivity and economics of sugarcane agriculture and ethanol production. Zabel[12] estimated that the cost of ethanol could be further reduced by the year 2000 by 17% to $0.16 litre from the current estimated cost of $0.20 litre in Sao Paulo State. (Table 2).

The costs of ethanol production could be further reduced if sugarcane residues, mainly bagasse, were to be fully utilized as has been shown by Ogden *et al.*[13] With sale credits from the residues, it would be possible to produce hydrous ethanol at a net cost of less than $0.15/litre, making it competitive with gasoline even at the low pre-August 1990 oil prices. With the biomass gasifier/intercooled steam-injected gas turbine (BIG/ISTIG) systems for electricity generation from bagasse, they calculated that simultaneously with producing cost-competitive ethanol the electricity cost would be less than $0.045/kWh. If the milling season is shortened to 133 days to possibly make greater use of the barbojo (tops and leaves) the economics become even more favourable. Such developments could have significant im-

Table 2. Estimated future costs and revenue requirements of hydrous alcohol production from sugar cane in Sao Paulo State, Brazil.

	Sub-total	Total
1. Raw material costs (US$/t)		
Cultivation		0.846
Preparation of soil	0.288	
Planting	0.557	
Plant protection		1.400
Seedling	0.097	
Ratoons	1.303	
Collecting		1.771
Cutting	1.600	
Loading	0.171	
Raw material cost at the field's level		4.016
Transport		0.821
Raw material costs (on-company's production)		4.837
Participation of suppliers' cane: 30%		
Price of suppliers' cane (after sales tax): 8.155		
Total raw material cost		5.832
2. Distillation costs (US$/l)		
Raw material	0.078	
Industrial labour	0.011	
Materials and maintenance	0.017	
Depreciation/industrial plant	0.010	
Electric power	0.003	
Total direct costs		0.119
Administrative and indirect costs		0.004
Taxes and charges		0.003
Total operating costs		0.125
3. Opportunity costs (US$/l)		
Return on land	0.009	
Return on investment		
Buildings and physical infrastructure	0.014	
Machines and fleet	0.022	
Industrial plant	0.021	
Return on working capital	0.004	
Total opportunity costs		0.071
Break-even revenue requirement		0.196
4. Sources of revenue (US$/l, after sales tax)		
Hydrous alcohol		0.180
Rind fibre (bagasse)		0.002
Gross profit/loss (revenue minus operating costs)		0.057
Net profit/loss (revenue minus total costs)		−0.014

Source: Zabel, *op cit*, Ref 12.

Notes: 1. Base case: agricultural productivity 75t/ha; sucrose content (quality) 14 pol-%; industrial productivity 75/t; industrial efficiency (extraction, fermentation, distillation) 75%; stream factor (production period) 0.4; production capacity (cane crushed: 8 000 t/day) 600 000 l/day; number of cuts/vegetation cycle = 5.

Zabel's simulated scenarios show the following results: variation of breakeven-revenue requirement ($/l, number of scenario in parenthesis):

	75 t/ha	82.5 t/ha	90 t/ha
75 l/t (14%-pol/t industrial efficiency 75%)	0.196 (base case)	0.193 (s2)	0.192 (s3)
80 l/t (14%-pol/t industrial efficiency 80%)	0.184 (s4)	0.181 (s5)	0.180 (s6)
85 l/t (14%-pol/t industrial efficiency 85%)	0.173 (s7)	0.171 (s8)	0.170 (s9)
90 l/t (14%-pol/t industrial efficiency 85%)	0.166 (s10)	0.163 (s11)	0.162 (s12)

1. The total private costs can be reduced from 0.20 to 0.16 US$/l (static analysis at a constant dollar rate, 3/86, 1 US$=13.84 Cz$).
2. Forecast for an overall cost reduction of approximately 17% in the middle term (by the year 2000), or 1.5%/year.
3. Considering the official price for hydrous alcohol (3/86) of 0.18 US$/l and 0.002 US$/l for rind fibre; break-even production 6 600 litres/ha; compared to an existing present average yield of 5 847 l/ha.

The true cost of gasoline production in Brazil is difficult to determine (mainly because of the lack of an open information policy by the oil monopoly Petrobras, and also due to factors as domestic oil production, refinery profile, export of gasoline to the USA).

1. Assuming the physical equivalency of substituting hydrous alcohol for gasoline of 1.25, current (1990) Rotterdam crude oil prices about 18 US$/bbl, and a ratio between gasoline and crude oil prices/bbl of 1.3 (which covers freight and refinery), even the most optimistic scenario would not presently be competitive, but would approach 30%. Actual motor gasoline price (regular unleaded, fob Rotterdam) of about 194 US$/t, equals 23 US$/bbl gasoline.
2. Because of the uncertainties in the forecast of crude oil prices, it is difficult to make any predictions about the future actual competitiveness of fuel alcohol; mogas prices (regular unleaded) must reach 268 US$/t (32 US$/bbl), or 25 US$/bbl for crude oil to achieve economic viability.
3. Considering two projections of CEC consultants, assuming a recovery and an unstable scenario, crude oil prices would rise to the level of 22 or 28 US$/bbl, respectively, in constant 1986 US$, by the year 2000. In the latter, fuel alcohol would become competitive within this time period, the former would approach 10%.

plications for the overall economics of ethanol production.

In 1989 proAlcool received severe criticism, with many voices calling for its reduction or even total dismantling.[14] The main reason was the sharp drop in oil prices which made alcohol fuel look like an expensive and even wasteful fuel. The situation was made worse when a severe shortage of alcohol fuel occurred in May 1989. Although the government blamed a drought in the northeast sugar producing regions for the shortfall, part of the crisis stemmed from bureaucratic and technocratic shortcomings. For example, fuel consumption was greatly stimulated when prices were frozen by the Summer Plan (a Federal economic anti-inflation programme launched in January 1989) and by the stagnation of alcohol prices both of which discouraged the distillers from producing more alcohol.

The economic and strategic arguments which formed the cornerstone of the original programme no longer seemed to apply when viewed against current international oil prices and the steady growth in Brazil's domestic petroleum production eg about 212 million barrels in 1988 at an estimated cost of $20/bb *v* an 'estimated cost' of alcohol of $45/bbl according to Young.[15] Government policies of maintaining low alcohol prices relative to the cost of gasoline could be seen to have backfired as they were not accompanied by sufficient incentives to expand alcohol production.

This new reality faced the government with difficult policy choices. Some policy changes contemplated included a reduction in the alcohol content in gasoline from 22% to 18%, a decrease in the retail differential between gasoline and alcohol from 60% to 75%, and a proposed reduction in the manufacture of alcohol powered cars to between 30 to 50% of all new vehicles. (See Table 1.) These last two measures posed the greatest long-term threat to the future of ProAlcool.

In addition, the surge of sugar prices in the international market in 1989, and the shift by farmers to other more profitable export commodities, has shown the vulnerability of the programme to short-term market fluctuations. For example in 1988, the government was forced to import 200 million litres of methanol and ethanol to fill the fuel ethanol shortage. Whether the trend to lower use of ethanol-fuelled cars will continue, considering present low oil prices and government's attempt to reduce subsidies for ethanol production is uncertain.

Brazil's alcohol programme crisis has many international as well as domestic implications. Abandoning ProAlcool, or even down-playing it, could mean a great increase in Brazil's capacity to produce sugar (Table 1) which could have serious implications for the world sugar trade. If the entire sugarcane harvest, for example, were turned over to sugar production, there would be a potential for producing over 21 Mt of sugar. It was ProAlcool in part that pushed international sugar prices upward in the 1980s after a decade of slump. A new export policy would flood the international sugar market, which would have serious economic consequences for cane-growing developing countries which are already calculated to be losing $7 billion in sugar export earning annually as a result of trade barriers in industrial countries.[16]

Many of the problems with ProAlcool are blamed by the industry on two culprits: the Institute of Sugar and Alcohol (IAA), which in June 1989 finally lost its 56-year monopoly over the country's sugar industry, and Petrobras, the state oil monopoly. The first created a price production stalemate by not correctly evaluating price levels for sugarcane and alcohol; and, the second, with its long standing opposition to the alcohol programme, would not help if it could avoid it eg payment delay tactics to distillers which in an economy with very high inflation rates results in large financial losses to the alcohol producers.[17] Petrobras' opposition to ProAlcool stems from concern with losing its monopoly of liquid fuel supply and also because the company made large investments in fluid catalytic crackers (large refining installations that convert residual fuel oil into lighter distillates, especially gasoline) which increased the proportion of gasoline obtained from oil. This resulted in large surpluses of gasoline which have to be exported at low prices.

Overall, Brazil's success with implementing large-scale ethanol production and utilization has been due to the combination of factors which include: government support and clear policy for ethanol production; economic and financial incentives; direct involvement of the private sector; technological capability of the ethanol production sector; long historical experience with production and use of ethanol; cooperation between government, sugarcane producers and the automobile industry; and, a well established and developed sugarcane industry which resulted in low investment costs in setting up new distilleries. In the specific case of ethanol-fuelled vehicles, the following could be cited: government incentives (eg lower taxes, and cheaper credit); security of supply and nationalistic motivation; and, consistent price policy which favoured the alcohol-powered car.

Thus, although an outstanding technical success, ProAlcool ran into serious economic problems when oil prices unexpectedly plunged in the mid-1980s. The Brazilian experience with ProAlcool shows the inherent difficulty of long-term energy planning; the decrease in oil prices, which once seemed only a distant possibility, may render obsolete all the projections on which the plans were based. As Weiss[18] points out the dichotomy clearly: 'on the positive side, Brazilian energy planners enjoy a substantial buffer against any possible future energy shortage, an advantage the rest of the world may some day come to envy. But as things now stand, the ProAlcool Program appears today to be an expensive and impossible-to-cancel insurance policy against an unlikely contingency'.

Zimbabwe: the Triangle Ethanol Plant

Zimbabwe is a good example of a country that has started to alleviate its liquid energy import problems by turning part of its efficient sugar industry to the production of fuel alcohol. An independent and secure source of liquid fuel was seen as a sensible strategy because of Zimbabwe's geographical position, the politically vulnerable situation, and for economic considerations. Because of its landlocked position Zimbabwe had to import petroleum fuels by means of a pipeline from Mozambique, or by road and rail through South Africa. Both means of import are subject to disruption. Petroleum imports account for 14% of Zimbabwe's energy use, and cost 18% of the country's foreign exchange earnings in 1984. The consumption of liquid fuel in Zimbabwe is relatively modest (but crucial to the running of a modern economy), with diesel now accounting for 55%, gasoline 32% (and the remainder kerosene) of the country's total liquid fuel consumption.

In November 1978, Triangle Ltd, a company involved in producing sugar and cotton, received the go-ahead to build a distillery at Triangle in south-east Zimbabwe. Triangle farms 13 000 ha of irrigated sugarcane plantations. The production of alcohol began in March 1980. The plant cost $6.4 million at 1980 prices – the lowest capital cost per litre for any ethanol plant in the world. The plant was financed mainly by local capital (one strict government condition was that foreign capital had to be recouped within six months by savings in foreign exchange) and home-based technology was required wherever possible rather than sophisticated equipment from abroad. All decisions concerning the construction of the plant were made locally. After considering a number of options, it was decided to build a standard batch-type fermentation plant. This process requires that tanks are emptied and sterilized after each fermentation, but the plant can be operated by existing staff at the sugar mill. The design was produced by foreign consultants, but the construction was carried out in Zimbabwe by a local project team. The consultants provided technical assistance where necessary, but a remarkable 60% of the plant was fabricated and constructed in Zimbabwe. Only specialist items such as plate heat exchangers, an air blower and instrumentation were imported. To ensure high standards, local welders were given special training. Few problems have been experienced so far; only the fermentation tanks have experienced corrosion problems.

The distillery was attached to a pre-existing sugar mill capable of producing cane juice and molasses of varying purities and concentrations to suit the needs of both the sugar factory and the distillery. The mill is powered from sugar cane bagasse during the seven month cane crushing season, and coal for the remaining five months. It was designed to produce 120 000 litres ethanol/day, with, on average, one tonne of sugar cane giving 125 kg of sugar and 7.5 litres of alcohol. Triangle also buys in cane from 150 local growers (small farmers and private companies) and molasses to supplement its own supplies.

With a realistic 96% time efficiency, and operating the distillery for 24 hours per day 50 weeks of the year, production amounts to 40 million litres per year. After nine years of operating experience, the expected output can be regularly achieved, or even exceeded as in 1986, when the plant produced 41.6 million litres of alcohol. However, the need to supply the increasing demand for domestic sugar can limit the output of ethanol when the cane harvest is low. Severe drought in 1987 reduced the output of ethanol to 37.4 million litres, and similar production levels were forecast for subsequent years for the same reason. After the addition of a small amount of benzol for adulteration, the alcohol is blended with gasoline. Initially this was a 15% alcohol/gasoline mix, but due to increased consumption, the blend is now about 12% alcohol. This is the only fuel available in Zimbabwe for vehicles powered by spark ignition engines.[20]

The area of land which would be needed to grow cane to provide enough alcohol to replace all imported gasoline and meet domestic sugar needs (but with none for export) is about 52 000 ha. This is less than double the total area now planted to sugar cane, and represents only 0.2% of available agricultural land in Zimbabwe. An alcohol programme that would power all Zimbabwe's cars with pure alcohol would not, therefore, necessarily compete for land with food crops. However, water for irrigation would be a problem.

Serious considerations have been given to the possibility of expanding both sugar and ethanol production. An integrated long-term plan has been drawn up allowing a flexible approach to changing variables. The expansion plan involves five phases the first of which starts with the opening of the Mushwe Dam in 1991, which will allow an extra 3 000 ha of cane to be planted; the ethanol plant could be extended to 50 million litres/year if there is no appreciable increase in demand for sugar. The second phase is also dependent upon the construction of the Tokwe–Mukorsi Dam (presently at the planning stage), which will increase substantially the water supply and will allow for a significant increase in the sugar growing area and eventually in ethanol production.

Triangle has overcome the stillage disposal problem by diluting the waste up to 200-fold with irrigation water. After cooling in ponds, the water plus stillage is applied as fertilizer to around 7 500 ha, about half of the sugar plantation. Although returning stillage to the land increases crop yields by 7%, care has to be taken not to damage the soil's nutrient balance. The stillage-rich irrigation water at present provides all the necessary phosphates, and an excess of potassium. The total value of potassium as fertilizer in Triangle's stillage is estimated at $1.1 million

Table 3. Barrels of oil purchased per tonne of sugar, and price per tonne of sugar, January 1973 to December 1990. Index: 1975 = 100%. (In US$ as priced at the time).

	Year 1973 (Jan)	1973 (Dec)	1975 (Average)	1982 (July)	1984 (Dec)	1989 (July)	1990 (July)	1990 (Dec)
Barrels of oil per tonne sugar	76.6	43.8	41.9	5.1	2.8	19.4	16.8	9.5
Compared with 1975	183%	105%	100%	12%	7%	46%	40%	23%
Sugar price \$ tonne^{-1}	230	224	401	115	80	301	269	218
Compared with 1975	57%	56%	100%	29%	20%	75%	67%	54%

Source: Scurlock, *op cit*, Ref 20.

each year. Alternative methods of making use of stillage and wastes are also being investigated. One practical method of disposal, for example, is to use the liquid 'wastes' to generate more energy by concentrating and then burning for heat and power generation. Alternatively, stillage could be anaerobically digested to make biogas.

Alcohol production in Zimbabwe reduces the amount of sugar available for export, and so reduces foreign exchange earnings. The sugar commodity market is notoriously prone to price fluctuations as can be seen in Table 3. In 1973 a tonne of sugar could buy 76.6 barrels of oil but only 2.8 and 9.5 barrels in 1984 and 1990, respectively. However, about half of Triangle's annual sugar production of 200 000 tonnes goes to the relatively unlucrative home market, and most of the rest is exported to the EEC under special trade agreements at around \$450/tonne. Any remaining sugar has to be sold on the world market. Zimbabwe's sugar has to be transported through South Africa for export, which reduces the price obtained by around \$100/tonne. Scurlock *et al*[21] discuss these economic factors in some detail. At November 1989 sugar and oil prices, ethanol cost fractionally more than imported gasoline. In August 1990 the price of gasoline was increased by about 50% since the country derived half of its oil from Kuwait.

Zimbabwe has proved that a relatively small country can diversify its agro-industry, to become less dependent on the whims of the external oil and commodities market. The country has now gained considerable experience in the building of fermentation and biotechnological industries, and when the strategic advantage gained from greater liquid fuel self-sufficiency is taken into account, the balance is firmly in favour of home alcohol production. From the outset Zimbabwe has maintained both local and national involvement in decisionmaking at all levels. Zimbabwe has pioneered the production of fuel ethanol in Africa, and provided valuable experience for other countries wishing to diversify their sugar industry to include fuel production.

The Pura village biogas project in India

In India there has recently been an emphasis on larger community sized digesters, of which there are around 25 now working nationwide. The Centre for Application of Science and Technology to Rural Areas (ASTRA) at the Indian Institute of Science in Bangalore has helped to build one such community plant in the village of Pura, some 200 miles west of Bangalore. Pura is a village of 430 people who together own 240 cattle. ASTRA initially thought that the manure from the village cattle could feed a biogas plant that would supply enough gas for all the village cooking needs, and the excess gas could be used for generating electricity for lighting and for pumping drinking water.

The plant began providing gas in 1982, but there were serious problems. The digester did not supply enough gas to cook both daily meals for every family in the village. The gas would invariably run out just before the second meal was cooked. Furthermore, anomalies became evident, eg small families who contributed little or no dung to the digester could manage to complete their cooking before the gas ran out. Although ASTRA had assumed that gas for cooking would be a priority, the villagers actually put clean drinking water at the top of their priorities. It was calculated that the digester could supply enough gas to power a generator to supply electricity which could then be used to pump water to a reservoir. However, villagers understandably wanted assurance that people would supply dung before they handed over their own valuable dung, whereas the project wanted assurance that people would supply dung before they set up the water pump. There seemed no way out of this impasse, and the biogas project stopped in 1984. Other aspects of help by ASTRA in developing the village nevertheless continued.

ASTRA tried to revive the project by suggesting that the generator could supply electricity for lighting. Less than haIf the 80 households are connected to the main electricity grid, which often does not supply sufficient electricity to power their fluorescent tube lights. However, the villagers were adamant that they wanted water. The project duly set up eight public taps connected to a reservoir fed by the electrically-pumped water. Excess electricity was used to power domestic lights, for which the recipients pay. Equity is maintained by keeping records of the weight of dung delivered and compost received for each family. These records are displayed publicly for all to see. The system appears to work well. It is now managed by the villagers, who are planning to increase the number of lights in homes, and provide more water taps. One resident is quoted as saying 'The grid provides government power, but biogas provides people power, which is far more reliable'.

Pura is now thinking of building a wood gasifier to provide producer gas as a supplement to its supply of biogas. Their gasifier would be similar to the successful project in the nearby village of Hosahalli which provides electricity for lighting and water pumping. Hosahalli has established a 2 ha woodlot to provide the feedstock. This means growing trees on a small-scale to feed the gasifier; but worldwide, such tree planting schemes have generally been a failure, with a few notable exceptions such as eucalyptus plantations in Ethiopia. Fuelwood plantations have run into many problems; they rarely produce fuelwood itself as the wood is more valuable for other purposes such as timber and pulp; women, the collectors and users of fuelwood, rarely benefit from plantations because such projects tend to plant trees on land owned by the more well-off men; plantations can often reduce the quantity of fuelwood available to local people, as foresters tend to restrict access to planted areas and thus the wood is no longer a freely collected resource, and has to be paid for.[22]

In Pura, however, ASTRA is confident that the villagers will grow trees specifically for the gasifier, having seen a nearby success and themselves wanting more electricity for other tasks. It was possible to set up the biogas plant in the first place because the villagers had nothing to lose by participating in the project. Women already collected the dung for use as fertilizer; the project merely 'borrowed' this dung and returned an equivalent quantity of compost, which is perceived as an improvement on the original manure. Once villagers experienced the benefits of the gas – clean drinking water from taps, and a reliable source of electricity – they were willing to take responsibility for the running of the digester, and ensuring that the benefits were distributed fairly. Residents now realize that biogas has raised their standard of living by making their lives more comfortable, so they will ensure that the system is maintained; this is a good illustration of the meaning of sustainable development. The producer gas should be able to raise the standard of living in Pura still further. It could release some of the valuable biogas for cooking, for example, or provide power for local industries. There will be a direct incentive to villagers to grow wood and maintain the woodlots specifically to feed the gasifier.

The Baringo project in Kenya

The Baringo Fuel and Fodder Project (BFFP) operates in semi-arid, degraded land around Lake Baringo in central Kenya. Its long-term objective is to have the excessive erosion in the area by revegetating with trees which are valuable for fuel and fodder, and grasses useful for feeding livestock and for thatching. Rehabilitated areas will be managed locally by representatives from the families who live nearby and use the fields.[23]

Not one project initiated in the Baringo area between the 1920s and 1960s appears to have survived. Some of these projects were initially successful in revegetating the land, but they failed because there was no local management structure to take over when outside assistance came to an end. But the priorities demonstrated by development projects are not always those shown by the people of Baringo. Evans[24] carried out a survey designed to determine the problems of the area as perceived by the people of Baringo. The results showed that the priorities of the local people were as follows: water for people; water for livestock; insufficient food; lack of job opportunities; lack of livestock markets; lack of veterinary advice.

Food and water for people and livestock are a continuing problem for subsistence agropastoralists living in harsh semi-arid conditions. The importance given to livestock reflects their dependence on animals for their livelihood. The high priority given to jobs indicates how important cash has become. The priorities of outsiders focuses on prevention of erosion and rehabilitation of land, while that of local people centres on securing daily needs.

The project has now functioned for over nine years, during which time it has developed social, managerial and technical strategies for rehabilitating denuded land. To begin with local people were highly sceptical that anything could grow on such poor land. It was important to first demonstrate that the project could plant suitable trees and ensure their survival.

In the first phase, therefore, the aim was to prove that it was technically possible to rehabilitate land with species that would provide basic resources. It is interesting that at this stage the project gave no quantitative estimates of what it would achieve over a given time, and neither of the donors (Beijer Institute, Sweden, nor the Netherlands government) stipulated such a requirement should be included in the project proposal. The initial aim was simply to prove that rehabilitation through planting useful species was possible. But planting 'useful' species implies that it is known what local people see as important daily requirements.

As Chambers has said, 'outsiders should not assume that they know what poor people want, but should undertake a persistent, patient exercise of asking them, and going on asking them, again and again.'[25] The BFFP is fairly unique in having a sociologist who carries out socioeconomic studies to learn the views and perceptions of local people. This social research is seen as an integral part of the project, and has had an enormous impact on its activities.

The project initially assumes responsibility for fields which it protects with fencing, and planting and maintaining the trees until they reach maturity. Local people then take over management of the fields to ensure that resources are harvested in a suitable manner. The project originally hoped that it would eventually become self-financing with the sale of products eg possibly charcoal. Experience has shown, however, that although local people can supplement their income from such sales, the money generated cannot match the costs of the inputs necessary for successful rehabilitation of the land. If it is necessary to provide economic justification for the project, then it is necessary to take into account the wider, beneficial environmental impacts.

The BFFP has clearly demonstrated that revegetation is feasible in the Baringo District. The project will now move from this experimental stage into its second phase, and will use the knowledge and experience gained in phase one to rehabilitate larger fields, and greatly increase the area of land planted with trees and grasses each year. Dissemination of information, and the training of local personnel and others are also a high priority.

To summarize, the aim of BFFP at the outset was to rehabilitate denuded land, while providing basic resources on an equitable basis for local residents. Unlike its unsuccessful predecessors, the initial work did not achieve quantifiable 'benefits', but was concerned with developing methods and technology to prove that these aims were viable in collaboration with the local people while taking their priorities fully into account. The importance of this experimental phase cannot be over-emphasized. If the BFFP had declared the ambitious intention of planting a certain number of hectares over a given period to produce a predicted quantity of fodder and charcoal, it would surely have failed to meet these goals. It is notable that it might have been much easier to obtain funding if the BFFP had made exaggerated promises. When, as is likely, these were not achieved, the project would then have probably been assessed a failure. Similarly, if the BFFP had forged ahead without understanding the needs of local people, it would not have gained the necessary local support.

Only now, some nine years later, does the BFFP have an idea of what is possible (and the considerable problems involved), and can, therefore, make goals that it can attempt to honour. This willingness on the part of the project to learn and to adapt has, of necessity, led to modifications of the goals and ideas to accomplish them. While the overall aim has remained the same, some of the original aspirations have changed. The ability to remain flexible, listen to suggestions and requests from local people, and learn from its mistakes is a fundamental reason why the BFFP has been successful so far. It illustrates how difficult it is to rehabilitate degraded land and that this is only feasible if it is socially acceptable in concert with the changing expectations, and also operating within the existing political decision-making process at all levels. Changes can be stimulated but only with the realization that biomass is one part of the overall problem of the development within given environmental constraints.

Conclusions

These last two examples of the BFFP in Kenya and the ASTRA project in India highlight the importance of social factors in energy programmes. At the same time as the social scene around Baringo is changing rapidly, the contributions from the anthropological data, including information on past events in the histories of the ethnic groups in the region, allowed the BFFP to achieve a fuller understanding of the authority structures and social customs of local people. Such sociological knowledge makes an important contribution to the success of the BFFP. But the project has also realized that it cannot be confined to the issues of fuel, fodder and environmental rehabilitation. As a consequence, over the years it had become involved in many other areas of development including employment, particularly women, creating dams to provide water for the people and cattle, making rural roads, training, education, and social welfare. In the Pura area ASTRA has also been involved in social and development issues. The problems encountered during the initial phase of the project were only overcome by listening to what the villagers said they needed. The project had to adapt to make the benefits be seen to be fair to all. Villagers also adapted by instituting a village committee to organize and administer the production of biogas, and the equitable distribution of the benefits. Pura had not had a village committee since before colonial days.

Biomass is the world's fourth largest energy source and the main energy sources in many developing countries. With an increasing proportion of the world's population residing in developing countries, who usually lack fossil fuels and the easy means to import such fuels, it is essential that greater effort be put into producing and using biomass efficiently as a fuel; it is an available indigenous energy resource which can be readily upgraded at all stages of production and conversion. The undeserved reputation of biomass energy as a poor quality fuel that has little place in a modern developed economy could not be further from the truth; biomass should be considered as a renewable equivalent to fossil fuels. If bioenergy were modernized much more useful energy could be extracted from biomass than at present, even without increasing primary bioenergy supplies.

There is a growing recognition that the use of biomass energy in larger commercial systems based on sustainable, already accumulated resources and residues can help improve natural resource management. If biomass energy systems are well managed, they can form part of a matrix of energy supply which is environmentally sound and therefore contributes to sustainable development as has been shown in the preceding case studies.

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Chapter 13

Renewable Energy in Rural Areas of Developing Countries

– some recommendations for a sustainable strategy

Hussein M. Rady

As analysis of the energy situation in rural areas in developing countries has shown that the major cause of the prevailing energy crisis is the shortage of organic fuel (biomass). To cope with this crisis, therefore, technologies must be sought either to enhance biomass resources or to substitute for them. As the majority of the population in rural areas are poor, the technologies applied should not only meet energy needs; they must also be geared to particular economic and sociocultural conditions. Technically efficient, decentralized systems for the utilization of renewable energy can help in this by raising the availability of organic fuel resources (biomass) and meeting the demand for higher quality energy. Despite their advantages, however, there has as yet been no widespread dissemination of these technologies. The main reasons for this are discussed, and some precepts are presented upon which, it is argued, a strategy for overcoming these obstacles should be based.

Keywords: Rural development; Technology transfer; Renewable energy

After four decades of North–South technology transfer, we are still a long way from finding satisfactory solutions to the economic, social and ecological problems in developing countries. Progress in the energy sector has been particularly poor,[1] although development planners and strategists in the industrialized and the developing countries alike agree that solving energy supply problems, especially in the poorer developing countries, would help overcome many other development constraints.

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Admittedly, the availability of energy alone will not solve the development problems of the developing countries concerned. Nevertheless, insufficient energy supplies, or rather the insufficient availability of energy, has not only been a crucial impediment to urgently needed economic and social development, it has also caused irreversible ecological damage, which could in future take on larger and uncontrollable dimensions. Obviously, moreover, energy is essential for the economic and social development of those countries where the technical, material, institutional and human infrastructure is in the initial stages of development.

The energy situation in most developing countries is in part paradoxical: on the one hand, there is insufficient energy available; on the other, the available energy is used wastefully and irrationally for lack of knowhow, which exacerbates the energy shortage. The technology applied to convert primary energy to useful energy, for example, is very inefficient; this is not only the case in private households, where fuelwood is directly burnt for cooking in the 'three-stone stove', but also in the conventional combustion of fossil fuel or in the thermal generation of electricity. In addition, in some countries with energy shortages, there are enough fossil fuels or renewable energy sources locally available, but they cannot be exploited, or at least not sufficiently exploited, or used, because their exploitation and/or utilization is uneconomic due to world market prices.

Broadly speaking energy resources in the poor developing countries can be enhanced and secured by taking the following steps:[2]

- Rational and economic use of the energy resources available (applying more efficient energy conversion technologies to improve the efficiency of converting primary sources of energy into useful energy and by more rational utilization by the end consumer).

- Dissemination of modern, more efficient systems to utilize local renewable energy resources mainly on the basis of:
  - (i) decentralized small systems to keep costs, technology and environmental damage within manageable bounds;
  - (ii) improved indigenous or traditional technology, and/or appropriate or modified imported technology to be produced locally with indigenous materials and operated by native personnel where possible.
- Greater afforestation and reafforestation to raise the production of fuelwood.
- Intensification of the exploration for and exploitation of fossil fuels to reduce dependence on imported fossil fuels.

These and other measures can be carried out, of course, only where there is a suitable and operational technical, economic and social infrastructure with sufficient capital and political backing.

This paper addresses in particular the first and second of these broad requirements. It outlines some of the root causes of the existing energy crises in developing countries, and identifies some of the factors which are driving the situation. It then attempts to formulate some precepts upon which a strategy can be formulated for the dissemination of technologies and systems for a rational use of renewable energy in the extremely poor areas, bearing in mind in particular the economic and social conditions that prevail.

CAUSES AND IMPACTS OF THE RURAL ENERGY CRISIS

Present and future energy needs in developing countries are generally different in urban areas from those in rural areas.[3] In urban areas, the bulk of the energy used is commercial energy, which is itself largely made up of petroleum products. The urban energy crisis is therefore best described as an oil crisis. By contrast, in the rural areas of developing countries, where the majority of the population still live, the largest energy consumption is of biomass in the form of fuelwood, dung (animal excrement) and crop residue.[4] Since the bulk of this energy supply is fuelwood, which has become increasingly scarce, the rural energy crisis has been called the fuelwood crisis.

This so-called fuelwood crisis, which is mainly the result of ruinous exploitation and complete deforestation, did not occur suddenly; it proceeded continuously and unobserved over the course of time. In the beginning, small clearings emerged on the outskirts of settlements, small patches, which then grew, finally joining together; wood supply came to an end in the surrounding settlements and eventually even in whole regions, which had previously had a surplus of fuelwood. The fuelwood crisis – or, more broadly, the biomass crisis – was mainly caused by the following:

- rapid growth of the rural population, and the resultant increased consumption of fuelwood, or biomass;
- poverty of the rural population and the consequent lack of purchasing power to pay for an alternative fuel;
- underestimation of the crisis and the overestimation of the means of containing it through (then) cheap petroleum (kerosene); and
- lack of or insufficient reafforestation and/or afforestation.

These factors have resulted in a vicious cycle of resource depletion in rural areas of developing countries (Figure 1).

As the declining wood yield of the forests could no longer meet the fuelwood requirements of the rapidly growing rural population, instead of planting new trees, the population began to cut them down without reafforesting. This uncontrolled overexploitation caused extreme soil erosion and related impacts, thereby exacerbating the dramatic shortage of fuelwood, which has totally disappeared in some areas. With the increased shortage of fuelwood, which had till then been regarded as common property, the population searched for alternative energy sources that could meet their energy requirements. One of the alternatives found was to burn animal excrement – dung cakes – and woody crop residues (residues containing lignocellulose), such as cotton stalks, corn stalks and cored corn cobs. The increased burning of dung displaced its use as an organic soil conditioner and/or fertilizer and thereby downgraded soil fertility. Lower soil fertility brought about lower agricultural yields ie a reduction in food and fodder production with its ensuing consequences: a food crisis and a decrease in dung production.

In an attempt to compensate for the low yield achieved per unit of arable land, farmland was simply enlarged. As arable land could not be en-

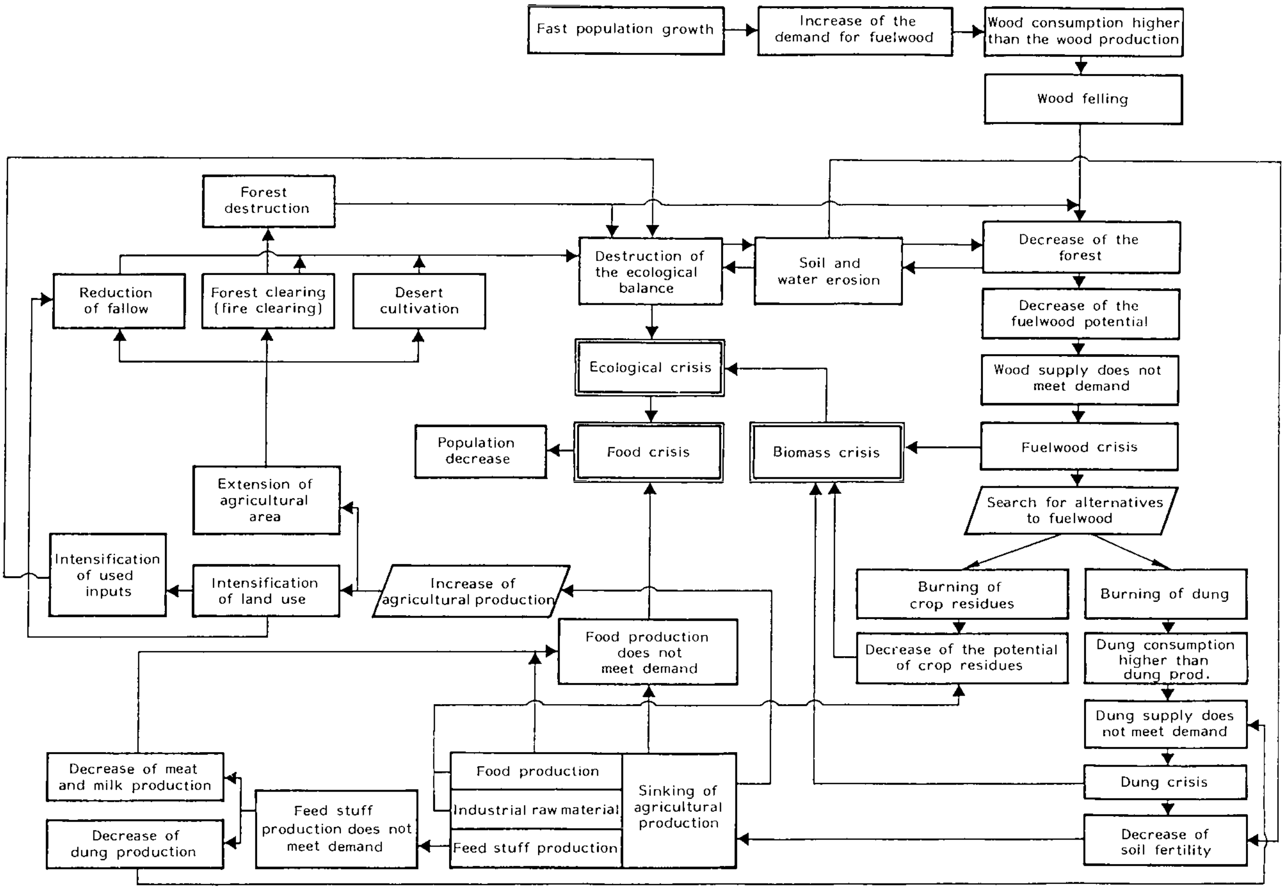

Figure 1. Vicious cycle of biomass crisis in rural areas of developing countries.

larged indefinitely, this expansion was at the expense of the forests and woodlands, initially in the valleys and eventually on the mountain slopes. What followed was a dramatic contraction of forest land, resulting in increased soil erosion, so that even more forests and arable land were destroyed. The effects were, among other things, a shortage of biomass and food and an ecological crisis (Figure 1).

The decreasing agricultural yield also led to a reduction in the land used for fodder cropping and to a decline in agricultural byproducts, so that altogether there was less fodder for the livestock. Livestock consequently produced less dung, which was needed both to substitute for increasingly scarce fuelwood and as an organic fertilizer for the conservation and/or improvement of soil fertility, so that the drive intensified to create more farm land to compensate for the decreasing agricultural yield per unit. Equally less milk and meat were produced, so that the food shortage became increasingly acute.

These many vicious cycles (fuelwood crisis – > ecological crisis – > food crisis), began with the apparently harmless shortage of fuelwood, but eventually spread to affect all rural activities. They highlight how serious the rural energy crisis and its consequences are; they threaten not only economic growth, but also the survival of the rural population in developing countries.

POSTULATES FOR ENERGY PLANNING

The following postulates provide both a brief outline of the energy situation in developing countries and also the starting point for energy supply planning generally and renewable energy planning in particular.

- Average energy consumption per capita in developing countries is in general lower than that in industrial countries, especially in rural areas. In future, therefore, a growing energy consumption can be expected over the entire spectrum of economic and social activities in both urban and in particular in rural areas.
- The share of energy from biomass compared with the whole of primary energy consumption

of the developing countries is over 50%; in some poor developing countries it is much higher.[5] In general, the higher (lower) the income per capita, the lower (higher) the share of biomass energy in total energy consumption.

- The share of biomass in energy consumption in rural households is extremely high, in some areas as much as 100%. This biomass is generally burned in simple fireplaces eg the traditional 'three-stone stove', with an efficiency of only about 10%.
- The utilization of renewable energy sources in rural areas of developing countries is not new. To date, such sources have been exploited using traditional, simple and inefficient technologies. What is new is the introduction of technically efficient systems that enable renewable energy sources to be used more effectively than hitherto and to be converted into high-quality energy, which was not possible with traditional technologies.
- Electrification in rural areas is extremely low.[6] Where a village is registered as being connected to an electricity grid, this is by no means an indication that the majority of the households in this village are supplied with electric power. Frequently, only a few communal facilities in the village have electricity.
- In rural households that can afford subsidized electricity, electrical energy is mainly used for lighting and for powering such appliances as radios, televisions, irons, hair-dryers etc thus improving quality of life, but seldom providing basic energy needs.
- For reafforestation and afforestation, considerable capital and an operational infrastructure is needed with tree nurseries to provide cuttings, seedling, plant, tend and protect saplings; but also, the trees take time to grow and provide fuelwood.
- It is often not economically viable to supply rural and remote areas with grid electricity, because the necessary investment costs are beyond the financial resources of these countries and because the energy consumption, or rather the density of energy throughput, in these areas is far too low for a grid system.
- Petroleum as an imported energy source does not pose a long-term solution because of price fluctuations and shortages.
- Energy consumption in low-income developing countries as a whole and per capita will increase at a rate higher than that of the gross national product as a whole and per capita.
- The need for fuelwood or biomass will continue to increase, even if its share of the total energy consumption diminishes with rising income.
- The expected growth rate in demand for commercial energy, especially for electricity, is higher in some areas than the growth rate in biomass requirements. But this should not create the mistaken impression that the supply of commercial energy is more important than the supply of biomass.
- The current, comparatively low, oil prices have at best eased the fossil fuel crisis or oil supply to the developing countries, but they have by no means solved it.
- Energy supply and the related technologies have to date been more or less decided by women. This will also be the case for future energy supply, both in rural and urban households. Any energy strategy that does not adequately account for the (disguised) power of women in the household will miscarry sooner or later.
- Energy strategies implemented contrary to the opinions or convictions of local administrators in the urban power centres and/or provincial administrative bodies are also bound to fail sooner or later.
- Innovative systems to utilize renewable energy resources will only be accepted and applied in rural areas as environmental technologies when they also address the present energy problems facing the rural population.

TOWARDS A SUSTAINABLE ENERGY STRATEGY

Given the energy situation as outlined above, the question that needs to be posed is how a rational system to utililize renewable energy sources can help meet present and future energy needs. First, it must, however, be taken into consideration that the new technologies for the utilization of renewable energies are at various levels of development.[7] There are some well established technologies, where the teething problems have now more or less been solved; others have already reached an advanced level in research, but still have to be practically tested as pilot plants. Finally, there are technologies which are in the early stages of research. It is evidently difficult, however, even for mature technologies to establish themselves on the market in the sense of widespread dissemination. There are several reasons for this, such as the relatively high initial investment (capital cost), misgivings as to reliability and cost effectiveness, insufficient familiarity of the native technicians and craftsmen with the technology concerned, insufficient awareness of the advantages of these technologies, lack of training, especially in environmental conservation and appropriate technologies, and an absence of understanding on the part of the political decision makers about the possible role and contribution of renewable energy.

Questions of economic cost effectiveness and the problems of financing are discussed in some detail below. First, however, I want to set out several aims which I believe a sustainable energy supply strategy, wishing to satisfy energy needs in rural areas, must pursue.

- It must meet present and future demand for biomass as a traditional energy in the form of fuelwood, charcoal, dung and crop residue.
- It must substitute imported energy, such as petroleum, with indigenous renewable energies.
- It must also ensure rational and economic use of imported petroleum, especially in the oil fired thermal generation of electricity.
- In areas where the supply by means of conventional energy systems is not economically feasible, is insecure and/or impracticable for other reasons, decentralized energy systems should be applied for the rational use of local renewable energy to meet the energy needs.

In fulfilling these aims a variety of technological options are of course available, including the following:

- a higher efficiency in the direct burning of biomass when preparing food eg by substituting the traditional 'three-stone stove' with improved or more efficient ovens;
- a higher level of efficiency in converting wood to charcoal;
- agricultural byproducts ie field and crop residues, can be converted into biocoal, hence substituting charcoal production.
- dung can be used as a source of energy and as a fertilizer and/or soil conditioner: this is made possible by using biogas technology in which the excrement can be decomposed via anaerobic fermentation into a gas mixture (biogas) made up of two-thirds methane and one-third CO_2, while retaining nearly all nutrients and soil conditioners in the fermentation sludge;[8]
- biomass production can be raised by means of reafforestation and afforestation, especially with fast growing trees, which ideally grow in soil little suited or unsuited to agricultural use (food production);
- solar thermal systems eg to heat water, dry agricultural products, desalinize water, for cooling purposes etc;
- photovoltaic generators for small and average power ranges, up to 10 KW eg for lighting, cooling, water pumping and even for fully decentralized rural electricity supply;
- wind converters to pump water and generate electricity etc;
- hydroenergy to generate electricity etc.

There are, then, a multiplicity of options for raising energy resources and a strategy for a sustainable energy supply should accord those options precedence that meets needs at the lowest cost for society. It is generally better for the environment and the economy to enhance energy resources by using the available sources more efficiently than by creating new ones. In their efforts to enhance or secure energy resources, therefore, the developing contries should accord higher priority to technologies for the more efficient utilization of the resources available than to those for the production of new forms or the provision of new sources of energy. The frequently encountered argument that because developing countries consume comparatively little energy they can also save little, does not detract from the relative advantage of technologies that use energy more rationally. This holds in particular for the neediest sections of the population, who burn fuelwood directly in traditional ovens with an efficiency of some 10%. If through improved technology the efficiency of traditional wood burning could be improved by, say, a mere 5 percentage points (ie from 10 to 15%), the improvement would raise fuelwood energy resources in rural areas worldwide by 50%. A comparable result by means of afforestation would entail considerable capital investment and knowhow and take a long time until the saplings can provide the requisite fuelwood yield and also until the countless cuttings can themselves be provided. Both approaches must, of course, be adopted in the long run, but the technology to improve the efficiency of traditional fuelwood burning is likely to be quicker and cheaper both to disseminate, and in satisfying energy needs.

Apart from a few exceptions, indigenous energy resources are mainly based on renewable energy; the costs of transferring and distributing energy are generally lower the shorter the distance between producer and consumer; energy density in rural areas is generally comparatively low. These are ideal conditions for applying decentralized energy systems to utilize the renewable energy sources available.

Obstacles and constraints

Serious constraints on the dissemination of renewable energy technologies and energy-efficient technologies remain, however. Like other innovations, new and improved technologies for the use of renewable energies are frequently caught up in a chicken and egg dilemma. As long as these energy technologies are not produced on a large scale they cannot compete with conventional technologies on the market. As long as there is no secure market, potential producers will invest capital neither in the manufacture nor in the development of these technologies, whatever their social or environmental benefit.

The main constraints to development of renewables in developing countries are economic, in particular the relatively high initial investment capital involved, and the disparity between economic viability and the population's low purchasing power. These financial obstacles will only be overcome by means of a specifically targeted national economic strategy. Although it is beyond the scope of this paper to provide a comprehensive strategy (indeed it is probably not possible to provide any meaningful common strategy given the diversity of situations), I would like briefly to highlight some basic facts concerning the situation and some underlying precepts for such a strategy, in particular, where economic and financial constraints are concerned.

The main obstacle to employing efficient renewable energy systems to satisfy the basic energy needs of the mass of the rural population is their absolute poverty; the poorer this population, the more difficult it is to introduce technical innovations, let alone to disseminate them on a commercial basis. Also, efficient energy systems are generally conditional on property and monetary income; these conditions are only partially met or are quite absent in a poor subsistence economy. These constraints should not, however, be understood to mean that efficient systems to use renewable energy are not suited to the rural poor and hence unable to contribute much to improving rural energy supply.[9]

Raising capital

Renewable energy systems are usually capital intensive. A viable financing model which can also be applied under adverse conditions is vital for the majority of potential users in the rural areas of developing countries. One reason for this is that when a potential user with relatively low monetary income buys a system on credit, he can face serious repayment problems, if he has not accumulated any savings or if unforeseen circumstances place additional burdens on his finances. Prior to the investment, he could have cut down on his energy consumption so as to adapt or to use the money saved to pay for other expenditure, but after purchasing the system he cannot do this: saving renewable energy, with its low or zero running cost, does not place any additional capital at his disposal.

Somehow, raising capital must be facilitated. By means of appropriate financing models, potential users barred access so far to the relatively high initial investment capital can be included in the user group. There are several conceivable ways of circumventing the high initial investment capital to the user.

Since the average potential user is more prepared or better able to pay fees rather than to invest capital, a possible approach might be for the governments in the developing countries concerned to instal renewable energy systems in villages, photovoltaic systems and/or biogas plant for example, and run these against payment, by charging for the electricity or gas used. This means that governments or other institutions in charge of energy supply should invest in and run systems for the utilization of renewable energy or act as suppliers of renewable energy against adequate payment.

Another conceivable approach would be to have the energy supply enterprises pay in advance for the renewable energy systems and have the user repay the initial outlay in instalments from the savings made in fossil fuel. This would only work if using renewable energy actually saved on fossil fuel; experience with individual cases shows that wealthier users tap renewable energy as an additional source ie when the wealthier section of the population use modern renewable energy systems, instead of saving fossil fuel, total energy consumption is raised. Leasing such systems could also help promote their dissemination. The systems could be subsidized in the introductory phase, although such subsidies should not exceed the anticipated economic benefit.

A frequent economic shortcoming of modern systems for the use of renewable energy is that the production cost per unit is usually higher than the price for the same unit derived from alternative fossil fuels, which are as a rule subsidized. Generally speaking, the economic competitiveness of renewables can be improved in a variety of ways, including:[10]

- reducing the production costs;
- improving the technical performance or efficiency;
- abolishing subsidies and other benefits for

competing fossil and alternative fuels; and

- using the saved subsidies from fossil and/or alternative fuels to help purchase renewable energy systems.

In particular, renewable energy could be made more economically viable by adding the social costs incurred by fossil fuels to the price.[11] This applies not only to the damage caused by emissions, climatic changes as a result of CO_2, but also and in particular the overall economic and social damage caused by the import of this energy. Such damage can only be roughly assessed and attributed to the perpetrators, but any price adjustment in the right direction is desirable and warranted.[12]

For all the possible or justified demands for suitable financing facilities, we must bear in mind that many countries in the Third World are unable to supply their own populations with food, so that governments are hardly in a position to provide large-scale financial support. Without outside support, via bilateral and/or multilateral technical and financial assistance, therefore, the scope for a rapid, widespread dissemination of modern systems for the utilization of renewable energy is, by definition, severely restricted.

In countries lacking capital, investments must, of course, be measured against the yardstick of economic efficiency or profitability. If, however, the concern is to satisfy basic needs ie the population's basic energy requirements, the economic aspect should not be the sole criterion, nor should it be the predominant decision making consideration. As experience has shown, long-term forecasting of price trends, especially in the energy sector, is beset with high risk and a number of uncertainties, so that economic reasoning alone in long-term energy strategy will not guarantee improved energy supply in the future. This does not invalidate economic efficiency as a criterion, but it does place limits on its scope.

CONCLUSIONS

This paper has addressed the underlying causes of the rural energy crisis in developing countries and laid out some of the conditions under which the implementation of renewable energy technologies must operate. It has highlighted some of the economic and social conditions governing the success of such initiatives.

Whatever the importance of the criterion of economic viability, its application as a sole criterion to the use and dissemination of modern renewable energy has its limits. In particular it relies on an adequate, competitive market and a level playing-field for renewables. Where renewables compete against imported energy generated by a technology that was massively subsidized in earlier years and is now produced on a large scale by a mature technology, the comparison is unlikely to favour renewables. Given the long-term environmental impacts of fossil fuels, and the social and environmental value of decentralized renewable systems, however, this kind of economic balancing is unlikely to lead to long-term sustainability.

If the energy source to be substituted has no market price, as is often the case, for example with fuelwood and/or dung, the economic feasibility calculation can only be made on the basis of shadow prices or opportunity costs of the substituted energy sources, which are difficult to ascertain and/or verify, so that the outcome of the calculation in such cases is beset with uncertainties.[13]

Economic factors are important, therefore, but should not override the long-term social and environmental value of disseminating renewable energy technologies. Where the concern is to satisfy the basic needs of the poorest section of the population, humanitarian criteria should replace economic ones. To ensure, however, that scarce capital is put to effective use, priority should be given to systems that constitute an improvement on traditional technologies. For example, if to date 'three-stone stoves' have been used, the population should be provided with better, more efficient stoves.

Where possible, a strategy for improving and securing energy supply should not be based on energy imports, but rather on self-sufficiency in energy. This self-reliance should not be confined to energy resources alone, but should also include the requisite technology and technological infrastructure for the conversion and utilization of these energy resources. This means that, wherever possible, a renewable energy strategy for developing countries should avoid replacing or substituting the current heavy dependence on petroleum imports with a dependence on imports of capital intensive and highly sophisticated technical equipment.

The most effective dissemination can be achieved initially by improving traditional technologies or by means of technologies based on traditionally available knowhow and not by ousting or replacing these.[14] The improvements aimed at bringing tangible benefits to the user should be attained without placing heavy demands or claims on him or her ie without completely disrupting his or her way of life and customs. Despite the prevailing poverty and the resultant scepticism towards every innovation, it is possible to introduce certain, simple but efficient and effective technologies in subsistence and poor societies and this is easier the closer these technologies are geared to the people and their needs as well as their economic, technical and social conditions and not vice versa.

[1]See G. Foley, 'Renewable energy in Third World development assistance', *Energy Policy*, Vol 20, Nos 4, 5, 1992; see also H.M. Rady, *Regenerative Energien für Entwicklungsländer* (Renewable Energy for Developing Countries), Nomos Verlagsgesellschaft, Baden-Baden, 1987.

[2]H.M. Rady, 'Strategie für die ländliche Energieversorgung in den Entwicklungsländer' (Strategy for rural energy supply in developing countries), *Zeitschrift für Energiewirtschaft*, Vol 15, No 4, 1991, pp 258–266.

[3]See, for more detailed discussions P. Pearsons and P. Stevens, eds, *Energy and the Third World*, Special Issue, *Energy Policy*, Vol 20, No 2, 1992.

[4]In some areas where no forest is available eg Egypt, the main source is dry crop residue, cotton and corn stalks.

[5]See D. Hall, 'Biomass', *Energy Policy*, Vol 19, No 9, 1991.

[6]G. Foley, 'Electrification in the developing world', *Energy Policy*, Vol 20, No 2, 1992.

[7]See *Energy Policy*, Special Issue, *Renewable Energy*, Vol 19, No 9, 1991.

[8]Considering that the biogas obtained can be used in numerous ways in the household eg for cooking and lighting, and on the farm, eg fuel for pumps and tractors, generating electricity or preparing animal fodder, biogas technology not only substitutes the direct burning of dung, thus contributing to the preservation and maintenance of soil fertility, but also substitutes the direct burning of fuelwood and crop residues, thus also helping to conserve forests/woodland. Furthermore, biogas can substitute for kerosene in rural households and diesel on farms, which contributes towards self-sufficiency in high quality energy and to easing the trade balance.

[9]Indeed, financial obstacles to renewable energy technology dissemination are by no means restricted to developing countries.

[10]*Op cit*, Ref 1, pp 473–482.

[11]O. Hohmeyer, 'Renewables and the full costs of energy', *Energy Policy*, Vol 20, No 4, April 1992.

[12]The frequently voiced demands for subsidies for modern renewable energy systems without changing price policy towards fossil fuel poses problems and could be detrimental to the image of renewable energies as a cheap source of power for the economy and the environment. The use of renewable energy should not therefore be made artificially cheaper than its actual cost; rather, the price of other sources of energy should be raised in line with their social costs, or else the economic viability of the new technology should be improved through lowering production costs or improving system efficiency.

[13]H.M. Rady, 'Cost-benefit analysis for road construction projects in developing countries', *Economics*, Vol 16, 1977, pp 63–72; H.M. Rady, 'Cost-benefit analysis for evaluating public projects', *Intereconomics*, Vol 4, 1974, pp 120–123.

[14]H.A. Havemann and H.M. Rady, *Technologiehilfe für die Dritte Welt: die Evolution der Entwicklungstechnick* (Technology Aid for the Third World: the evolution of development technology), Nomos Verlagsgesellschaft, Baden-Baden, 1979.

Chapter 14

Renewed Prosperity for the Country Boats of Bangladesh

Colin Palmer

The country boats of Bangladesh provide a vital transportation network in a country of waterways and regular flooding. Traditionally they have relied exclusively on renewable energy inputs for their motive power. In recent years they have suffered severe economic decline due to competition from trucks and buses running on new road systems. This decline has been reversed by the use of small diesel engines for propulsion. The boatmen are now enjoying renewed prosperity and enhanced social status, changes which could not have occurred if they had continued to rely on renewable energy sources.

Keywords: Transport; Wind power; Biomass

There was a time when traditional village life in Bangladesh might have been seen as an ideal model of a sustainable low energy existence. People were prosperous and all their energy inputs came from renewable sources, there was little waste and most things were recycled in one way or another.

This view can be supported by extracts from the pages of a fascinating report by J.C. Jack, of the Indian Civil Service.[1] In describing life in Bangladesh (then East Bengal) at the turn of the century, he said 'The life of a cultivator in Eastern Bengal is in many ways a very happy life. Nature is bountiful to him, the soil of his little farm yields in such abundance that he is able to meet all his desires without excessive work'.

One striking point about Jack's account is that in a section where he provides an analysis of family budgets, no mention is made of firewood or transport costs. Presumably all the wood that was needed for cooking was so readily available that it cost nothing and life was so self-contained that transport other than walking was unnecessary.

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Although not specifically mentioned by Jack, the main communication between the villages, other than by foot would have been boats. Bangladesh is a country of waterways and in the past they were almost the only means of long distance travel as well as providing a vital rural transport network. Even today, fewer than 25% of villages are directly served by road, with the remainder being reliant on boats or access on foot.

The traditional role of country boats

Historically the country boats were a relatively prosperous sector of the rural economy.[2] The boatmen were a proud and independent group with strong identities and respected positions in society. They lived a life that was self-sufficient and independent. Typically, they were free-ranging entrepreneurs who traded goods from one part of the country to another. They had the social standing that enabled them to obtain cargo on credit and take it to far off markets where they judged that it could be sold at a profit.

Their main sources of income were these profits on the goods which they traded. Their boats were simply the tools that they used to carry on this business. The upper limits to their incomes and prosperity would have been strongly linked to the credit which they could secure and their abilities as traders and businessmen. Their abilities as boatmen were secondary. They lived much more from the power of their intellect and social standing than from the power of their bodies.

The propulsion of the boats relied entirely on renewable energy inputs. The wind, the river current and the power of the crew to row or pull the boat from the bank. As the boat owner also owned the cargo, he could be the judge of how fast they should travel and how hard they should work. In this way, they could control how much of their own effort they expended and how much they waited for nature to provide.

Changing times and increasing poverty

Now times have changed. The boatmen's enviable economic independence has been eroded and their position in society has diminished. Their commercial power has been reduced so they have become heavily dependent on others as they have progressively lost control over the sources of their livelihoods. There are many historical reasons for this, details of which can be found in sources such as Greenhill[3] and Jansen *et al.*[4] The overall characteristics of the change are those of a once closed economic system being subjected to external forces beyond either its control or understanding. With the rise of world trade and economic interdependence, the rural transport of Bangladesh has become subject to the vagaries of world markets. More direct influences have been the rapid rise in the price of raw materials for boats (wood) due to deforestation and export demand. At the same time they have experienced increasing competition from heavily subsidized roads and government-backed water transport operations.

Whatever the reasons, recent studies, particularly Kvam[5] provide graphic evidence of their outcome. The great majority of boatmen now make their living by wage labour. Many boats are now owned by absentee owners, but even the remaining owner-operators mostly hire out their boats to carry goods that belong to others. All that they sell is the cargo-carrying ability of their boats. This relies heavily on their human labour as it can be no more than the product of the capacity and speed. The average speed is highly dependent on the amount of hard labour that the crew can provide whilst the capacity is fixed by the size of the boat.

The upper limit to their income is therefore much reduced. It is determined only by the carrying power of their boat and is thus limited by the level of human power inputs from the crew.

Thus, in common with many rural people in modern day Bangladesh, they have been reduced to selling their labour. Like agricultural day labourers, they sell the renewable energies of their bodies in an economy which offers little scope for their intellect and which accords them very lowly social status.

The renewable energy solution

These problems which are facing the boatmen have been studied by many consultants both from within Bangladesh and outside, eg Gifford and Howe,[6] Khan,[7] and Jansen.[8] During the 1980s the conventional wisdom (amongst non-boatmen) was that the best technical solutions lay in developing more efficient ways of using the renewable energy inputs to the boats. This involved proposals for improved sails and sailing techniques as well as techniques for more efficient rowing. Great emphasis was placed on the employment generation that would result from the continued use of these labour intensive methods. Most recently, this solution has also had the additional appeal of the environmental benefits associated with the use of renewable energy sources.

It is easy to understand the reasons for reaching these conclusions. The traditional sails are an impressive sight and under the right conditions they can produce a good turn of speed. True, they may appear antiquated when compared to the sharp triangles of modern racing yachts, but it is then a logical step to think that if the country boats were to adopt this technology they would be transformed into the same efficient sailing machines. Similarly, traditional rowing appears crude and wasteful to eyes accustomed to slender rowing shells complete with sliding seats and sculptured oars.

Unfortunately the reality is very different. For wind propulsion to work, there must be wind, but the winds of Bangladesh are generally very light and fickle.[9] No amount of high technology will overcome this fact. For rowing to work, there must be adequate muscle power. All other things being equal this is primarily a function of the number of men who can pull on the oars. For a boat operator, more men cost money.

Wind power

The winds in Bangladesh are light. Data published by Khan[10] indicates that in many places the annual average wind speed is much less than five knots. Wind roses for the country also indicate periods of calm ranging from 10% to 90% of the time, depending on the location and season. Figures of the order of 30% to 40% are very common. Calculations have been made of the potential sailing performance of typical Bangladesh boats.[11] The physics behind these calculations cannot be described here, but are very well covered by Marchaj.[12] One very important feature is that the speed of the boat varies not only with the wind speed but also with its direction relative to the direction in which the boat wishes to travel.

It is, for example, impossible for any sailing rig to carry a boat directly into the wind. Even the most efficient racing yacht cannot sail within 35 degrees of the wind, so there is a 'dead' sector of at least 70 degrees where they have to make progress by zig zagging back and forth – the slow process called tacking. For the traditional boats of Bangladesh, this

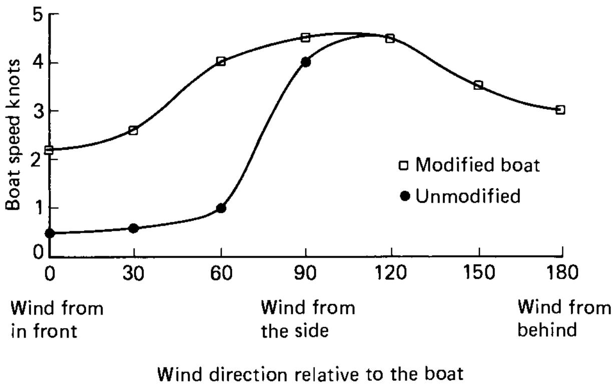

Figure 1. Variation of boat speed with wind direction (assumes constant wind speed of 6 knots).

dead sector frequently extends up to almost 90 degrees either side of the wind direction. This means that they can only sail when the wind is from the side or behind and so can make virtually no progress at all towards the direction of the wind. The combined effects of these influences is to make the input from the wind highly variable and unpredictable.

There are technical modifications which can be made to improve the sailing performance. In 1985 they were demonstrated on a boat called NOAMI 1.[13] This traditional country boat was equipped with the modified sails and lifting keels. In typical Bangladesh wind conditions, the sails could produce the power of eight or 10 oarsmen when the wind was from the side of the boat. (A boat of this size would have a crew of five, so the sails gave significantly more speed than the combined efforts of the crew on oars or tow lines.) The effectiveness of the sails reduced in other wind directions, down to only two or three oarsmen when it was least favourable. However, unlike most traditional country boats, NOAMI 1 could make progress in any direction, either directly or by tacking.

The experiment undoubtedly showed that there was technical potential for improving the way that the renewable energy from the wind could be used. Figure 1 shows the predicted sailing speed of NOAMI 1 before and after modification. It presents the speed as a function of the direction of motion of the boat relative to the wind direction. It can be seen that even for the modified boat, the variability in speed with direction is still considerable.

Human power

A fit, well-fed human being can produce an average power output of 150 to 200 watts. The difference in efficiency between the normal rowing methods in Bangladesh and a technically improved design could perhaps be 50%. In other words, for a crew of four oarsmen, their output might possibly be increased to be equivalent to six men.

At face value these potential improvements due to better use of the renewable energy sources of wind and human muscle power are promising. They can be shown to offer the possibility of increasing the speed of the boats by perhaps 50% to 100%. As the earnings of the crews could be predicted to increase, their economic decline might be halted without paying a heavy price in energy inputs.

The boatmen's reactions

Fortunately for their prosperity, the boatmen were not included in the development of these ideas, so they did not waste precious time and resources on experimenting with trying to make better sails or to improve their centuries-old techniques of rowing. What they were doing was what they had been saying they wanted to do all along – to fit engines to their boats.

Two particularly crucial points had been missed by most of the expert studies, but were starkly apparent to the boatmen:

1. The sector was losing out rapidly to trucks and other land-based transport systems. It was a matter of survival that they found a way to increase speeds by many times, not just 50%.
2. The traders who hired their boats were as interested in predictability as speed. The unpredictable increase in speed that would result from improved sailing performance was of little interest to them. They wanted to be able to specify the day when the cargo would arrive – for example to coincide with a market day. If the day was missed, the cargo would have to wait a week or be sold at a reduced price.

The boatmen knew their only chance of survival was to use diesel engines. Their problem for many years was money. Due to taxes, the price of suitable engines was generally out of their reach so in the early 1980s they made do with second hand engines of many different types. More recently a combination of increasing confidence in the returns from investing in an engine and the availability of low cost engines from China has resulted in an explosion in the number of mechanized boats.

The rise of diesel engines

From an almost insignificant number of mechanized boats reported in Jansen,[14] the proportion today has risen to more than 80% in some locations. Overall the average is around 60% and is increasing by the day.[15] These numbers represent considerable economic activity as well as rapid social and technical change. All the engine installations have been carried out by the boatmen themselves – financed from their resources and installed by their local workshops. No external agencies have been involved in any way at all.

No one knows the total number of country boats and estimates range from 300 000 to 1 million. For the sake of illustration, a figure of 500 000 boats is not unrealistic. On this basis, more than 250 000 engines have been installed in the last 10 years, with the great majority being fitted in the last three years.[16] If this is so, it represents an investment of around $100 million and a total installed power of 2 GW, all undertaken by an informal sector of the economy which is almost unrecorded in official statistics and unrecognized by officials or in development plans.

The advantages of diesel engines

So why are engines so important to the boatmen? For one answer we should look back to the illustration of the power of sails. In good conditions, a large, modernized rig could produce the effort of eight men, but the availability of this effort is highly dependent on the wind that happens to blow as well as its direction relative to where the boat has to go.

In contrast, even a very small diesel engine will produce the power output of 30 men. It produces it continuously without tiring or complaining and independently of wind speed or direction.

A comprehensive field survey of 205 country boat operations was conducted in 1990.[17] Amongst many other subjects, the boatmen were asked their opinions on the demise of sailing and the value which they placed on having an engine. None regretted the passing of sails. Close to 95% were positive to the idea of having an engine in their boats. Indeed, they were almost universally glad to see the back of sailing, something which they saw as outmoded, hard work and dangerous. One informant said:

If there is a sail, the passengers think that the boat's engine gives problems and for this reason the passengers are discouraged to hire the boat

The following quotes are also typical of the boatmen's opinions of engines:

The boat can go faster. Moreover, passengers prefer faster transport

It is problem to keep face with others unless the boat is fitted with engine

Quick transport is possible, a distance of 6 days can be covered in one day

It can save us from pirates and storm

The traders prefer engine boat. The trip which we cover in four days, now can be covered in a day

Ease of securing cargoes, increased safety and greater status might be a summary of these views. The comments about trip time reveal that average trip speeds have increased by factors of 4 or 6 – a far cry from the 50% speed increase that was predicted for a boat making the best possible use of renewable energy sources.

Costs of mechanization

The engines now used on the boats are simple Chinese diesel engines that were developed for agricultural use. It is indicative of the inventiveness of the boatmen that they have evolved ways of fitting them to boats and connecting them up to shafts and propellers with flexible couplings. A complete installation may cost Tk15 000 ($425). To put this in perspective, just the mast needed for a traditional sailing rig can cost Tk10 000. The sails and rigging double this figure. A new boat is in the range of Tk50 000 to Tk100 000.

Thus the fitting of an engine adds less than 30% to the cost of a new boat. Most striking of all, it costs significantly less than a new sailing rig.

Economic benefits

From the boatmen's point of view, the fitting of an engine brings great financial benefits as well as the practical advantages of greater safety, less drudgery and enhanced status. It has already been mentioned that traders prefer mechanized boats – not that they will pay much of a premium, but they give much greater preference to hiring mechanized boats. This means that mechanized boats get more cargoes and can make use of their increased transport capacity.

From analysis of the field interviews reported by Kvam,[18] it has been possible to deduce that the gross income for an average boat increased from Tk11 500/month to Tk20 500. It is tradition on the country boats that the crew's food is paid from the boat's income and that they are also paid cash sums calculated as a constant share of these earnings. Other shares go to the owner.

The effect of the share system was that the crew of non-mechanized boats were each paid an average of Tk685/month. After the fitting of an engine, the percentage share which they received actually decreased, but since the total was bigger the actual sum

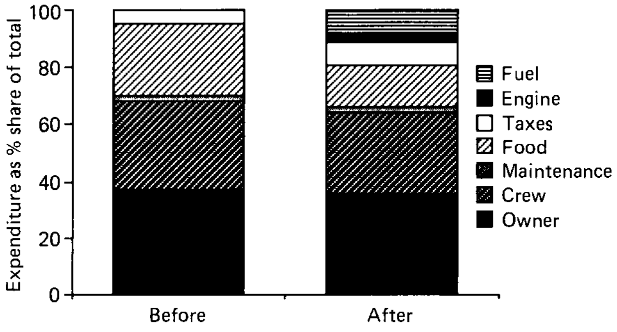

Figure 2. Effect of mechanization on share structure of country boat operation.

of money increased to Tk980 – a rise of almost 50%. These changes are illustrated graphically in Figures 2 and 3.

Too good to be true?

There is no such thing as a free lunch, so the saying goes. But if 50% more income and greatly reduced hard work are not a free lunch, who is picking up the tab? It is proving difficult to tell, but so far the results suggest that in practice there are few losers. Employment in the boats does not reduce significantly with mechanization, contrary to the dire predictions of the 'labour intensive' school of development. Maybe some trucks are loosing business to the boats, but there are also instances of their cooperation, not competition.

There has been some evidence that the 'formal' – ie capital intensive and government backed inland water transport has been reacting negatively. They are pushing for registration of the country boats and for regulations which will make them fit expensive equipment beyond the reach of most operators.

Overall though, none of these protests are very strong. The reality seems to be that the availability of faster, more reliable water transport has tapped into suppressed demand. New cargoes are travelling by water. Goods and people are making journeys which they did not make before and new economic activity is being stimulated. Small farmers can now use the boats to get perishable goods to market, where before they would not have bothered to grow them. The price differential between rural and urban areas is being reduced as the increased flexibility of the transport system allows goods to move more freely. None of these changes would have occurred without the use of diesel engines on the boats.

Energy considerations

The changes may have brought about improved incomes for the boatmen, but it is apparently at the cost of increased use of fossil fuels. Compared to the days of sail and oar, there is no doubt that the boats use more fossil fuel. At the most basic level, the power for the boats prior to mechanization was mainly the muscle power of the crew – a renewable energy in the form of men converting the biomass of rice to motive power. Despite the low cost of rice, this process is actually more costly than using diesel fuel as a source of power. The rice needed to sustain life is variously reported – 22.2 ounce (0.62 kg) per day in Taher,[19] 1.5 lbs (0.68 kg) in Jack[20] and 0.75 kg in Jansen.[21] Taking an average of 0.68 kg, this would cost Tk10 at prevailing prices (March 1991). At the same time, fuel costs Tk14 per litre. In a typical day's operation a total of 12 litres will be used. This costs Tk168, so is equivalent to the cost of rice for 18 people. In comparison, the actual motive power provided by the engine is equivalent to the output of 30 men, so even if men could be hired for just the cost of keeping them alive, an engine would still be a more attractive option.

A more realistic comparison from a boat owners point of view is that the cost of fuel is about the same as the total food cost and cash payments needed to keep an additional three crew members. It would be very clear to a boatman that a fossil fuelled diesel engine which produces the power of 30 men is a much more productive way to spend his money than hiring three additional crew members, even if their 'fuel' does come from renewable sources.

What about when fuel prices rise, the cry so often used to justify renewable energy projects? Fuel prices in Bangladesh have doubled since late last year – officially in response to the Gulf War. The country boat operations have continued unabated, an obvious reason being that before the price rise, fuel costs were only 8% of income, so even a doubling means that net earnings are still significantly more than they were before mechanization.

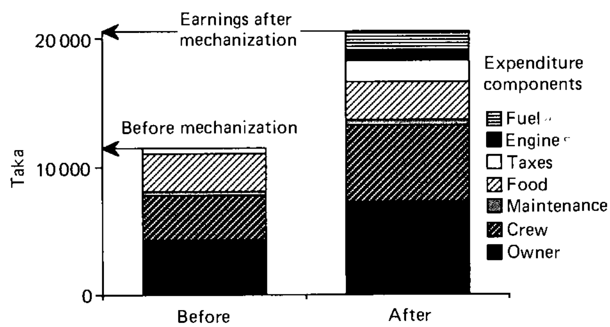

Figure 3. Effect of mechanization on earnings and expenditure.

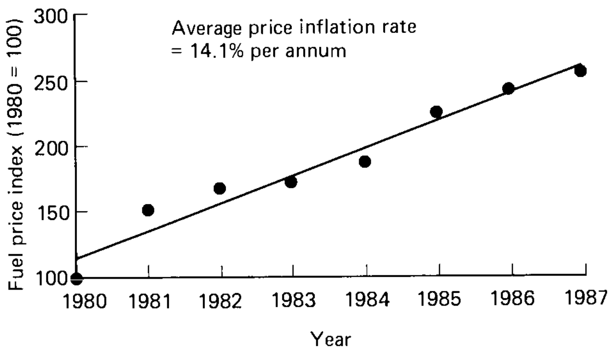

Figure 4. Price index – fuel and light.

Energy use by competing modes of transport

The most severe competition to the country boats comes from roads. (This unfortunately is not just in the direct 'open market' sense of trucks and buses running on the roads, but indirectly in so far as roads attract investment and so divert resources and official attention from the inland water transport sector.)

Studies[22] have shown that boats in their present form are 60% more fuel efficient than trucks on the basis of tonne miles of cargo carried. They also charge freight rates which are 35% less than a truck. On many routes they can provide a service which is as quick as that offered by trucks since road transport is plagued by delays due to ferries and circuitous routes, not to mention flooding and impassable roads in the wet season.

When compared to buses on arterial routes, boats are an unattractive means of transport. In rural areas, where the alternatives are rickshaws or 'Baby Taxis' running on bumpy or almost non-existent roads, the boats present a very viable option, particularly for trips to and from market, where goods have to be carried. In these roles they are significantly more fuel efficient than the petrol engined taxis.

Energy and road building

According to statistics in *The Human Development Report*,[23] Bangladesh is the country with the highest population density on earth (with the exception of 'city states' such as Singapore and Hong Kong). It also has a population which is predominantly rurally based and heavily dependent on agriculture and biomass fuel sources. 83% of people live in rural areas[24] and it is estimated[25] that in 1990, 70% of the total energy use in the country is biomass. (In rural areas the proportion of biomass will be higher than the average.)

The total fuelwood consumption in 1981 was estimated to be four million tonnes. At the time the population was around 91 million, so average per capita fuelwood use was 0.04 tonnes per year, which is only about 20% of normal needs – the remainder being made up from crop residues, twigs and leaves and animal dung.[26] This widespread substitution is an indication of the severity of the wood shortages. Price has been another indication of the high level of demand for wood. In the last decade, wood prices have increased at the rate of at least 25% per year, compared to 14% for other fuels and 11% for food. These trends are illustrated in Figures 4 and 5.

With such price sensitivity, competition for land use and biomass (renewable) energy sources can have a direct and strongly negative impact on the rural people, who also tend to be the poorest and least influential sector of society.

Road building is one such source of competition. In financial terms, road building in Bangladesh is unusually expensive. It takes scarce agricultural land out of production and the roads themselves need high embankments to resist flooding, many bridges and culverts for drainage and must be built to survive uncertain foundation conditions.

In energy terms it is also extremely expensive. Broken bricks are widely used in road building as other materials are not available. Bricks in Bangladesh are traditionally fired with scarce and valuable fuelwood (although recent legislation has sought to combat this trend by encouraging substitution with natural gas or imported coal). The analysis of energy use in Bangladesh based on 1981 figures[27] indicates that the amount of wood used for brick burning was very similar to the total use in rural cooking. Fuelwood is also used extensively for urban cooking as urban people have less access to alternatives such as crop residues and animal dung. Figure 6 shows the relative proportions of fuelwood use.

A typical road in Bangladesh uses 200 000 to 300 000 bricks per kilometre. As each brick needs 0.43kg of fuelwood, each kilometre of road uses

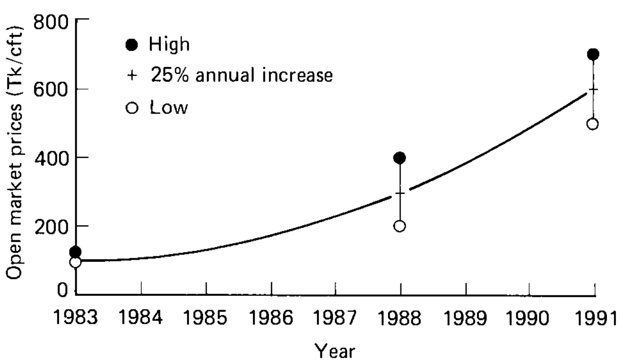

Figure 5. Market price of sundari wood.

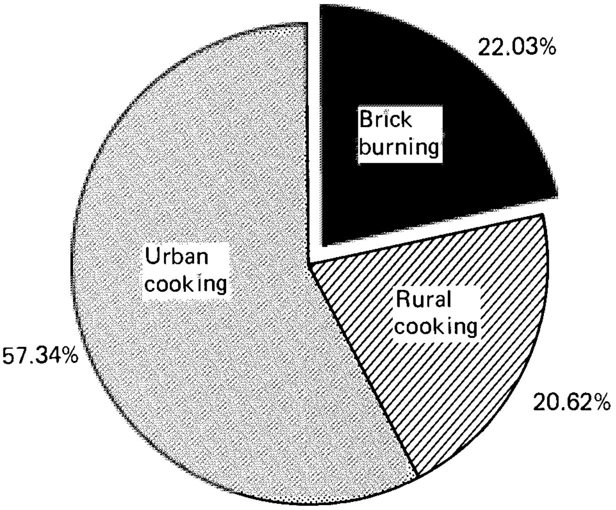

Figure 6. End use of fuelwood (1981 figures).

fuelwood which is equivalent to almost 3 000 people's annual domestic fuelwood consumption.

When a road is built, large amounts of renewable energy are locked up in its construction. This contributes to the rapid rise in wood prices and the deforestation of the country and the worst effects are borne by the rural poor, who are also the people who generally benefit least from the provision of roads.

It has already been shown that on the basis of operating costs to the owners, the country boats are more cost-effective and more fuel efficient than trucks. On a national policy basis, account should also be taken of the complete costs of the service, which includes providing the infrastructure as well as the actual transport service itself.

On this basis the large investments of financial and energy capital needed for roads adds a very significant cost. When this is combined with externalities such as loss of productive land and the environmental damaged caused by road building and their impact on drainage, the alternative of water transport by country boat becomes increasingly attractive.

In contrast to trucks, the boats do not need expensive infrastructure for their operation. The rivers already exist so there are no problems of land loss. There are places where the rivers can benefit from work such as dredging, but the costs are almost insignificant when compared to road building and do not involve energy intensive inputs. In addition to improving navigation, such measures also improve drainage, thus have a positive environmental impact.

Conclusions

The mechanization of the country boats in Bangladesh has reversed the steep decline of a traditional and vital sector of the rural economy. In addition, it provides significant practical and economic benefits to the owners and crews of the boats. This could not have been achieved by the use of renewable sources of energy.

The improved service which they are able to provide is maintaining employment and there is some evidence to suggest that it may even be stimulating new economic activity in the countryside. With mechanization, the country boatmen have a higher status in society and are able to offer a service which can be directly competitive with road transport. Road transport needs roads and road building in Bangladesh is very energy intensive. The alternative of country boats has the potential to reduce the need for new road building and so result in reductions in national energy-use.

The better operational fuel efficiency of the boats when compared to trucks also has significant implications for energy saving. The country is totally dependent on imports for its oil, but needs an extensive and reliable transportation network if future development goals are to be met. The waterways can provide this network in many parts of the country.

The current techniques used in the mechanization are very low cost, but this is achieved at the price of poor fuel efficiency. Unlike trucks, where there is little scope for change, there is considerable potential for further improvement in the fuel efficiency of the boats.

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Chapter 15

Renewable Energy in Third World Development Assistance

– learning from experience

Gerald Foley

The record of renewables in energy assistance over the past 15 years has been poor. The reasons include technical weaknesses, high costs and falling oil prices. The future role of renewables in development assistance remains open to debate. They should only be used when they represent the optimum technical and economic solution. Ensuring that this is the case will require considerably greater rigour in the technical and economic analysis of projects than in the past.

Keywords: Renewables; Development assistance; Policy

Energy assistance for renewable energy technologies in developing countries has had a depressingly poor record over the past two decades. Apart from large scale hydro, the number of renewable energy projects actually working is a small fraction of those undertaken. And among those working, the numbers economically justifiable or locally self-sustaining are smaller still.

All this represents a significant waste of development assistance funds. It is also a considerable waste of human resources in the development community – often those who are the most concerned and caring about human issues such as poverty. Above all, it is a waste of the scarce managerial and human resources of the developing world.

This paper examines the assumptions and attitudes which under-pinned the renewable energy assistance policies widely followed by the international donor community during the 1970s and 1980s and tries to explain why the results were so disappointing. It then attempts to look forward and identify the new approaches which will be required if the achievements of the 1990s are to be significantly better.

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THE ENERGY EVENTS OF THE 1970s

The energy assistance policies of the past 15 years were profoundly influenced by the energy events of the 1970s. These events not only transformed energy from a relatively obscure technical issue into a matter of high public and political concern but they also provided a major impetus for renewables.

Around the beginning of the 1970s, publications such as *The Limits to Growth*[1] and *A Blueprint for Survival*[2] were warning that industrial society was rapidly undermining itself through pollution and excessive use of natural resources. The 1972 UN Conference on the Human Environment in Stockholm strongly reinforced these environmental and resource depletion worries.

Energy came into the picture in a dramatic manner with the 1973 Middle East war which enabled OPEC to impose a sudden fourfold increase in oil prices. Many energy analysts concluded that the era of cheap and abundant oil was at an end and there were confident predictions that it would be selling at \$100/bbl by the year 2000. In addition, the media and popular 'ecology' books fostered a widespread impression that oil was on the verge of running out. *A Blueprint for Survival*, for example, predicted that oil resources would be exhausted by the year 2000.

Finding substitutes for oil became an urgent task for governments. Technologies for the manufacture of synthetic crude oil and gas were heavily funded in the USA, Japan, West Germany and elsewhere. Major efforts were made to develop ways of exploiting tar sands, oil shales and other unconventional oil resources. France viewed the energy future with equal concern but took a different approach and launched a massive centrally planned nuclear programme.

Interest in new and renewable energy sources, from the familiar wind and solar through to exotic technologies like ocean thermal gradients, grew rapidly. The Swedish Secretariat for Future Studies, for example, published a report in 1977 entitled *Solar Sweden*[3] which examined how Sweden could meet its energy needs from renewable sources. The United Nations resolved to hold a conference on New and Renewable Sources of Energy in Nairobi in 1981; one of its main themes was to be the particular relevance of small-scale renewable energy technologies to the developing world.

In 1979, came the Iranian revolution and its disruption of the country's oil production. The OPEC decision to take advantage of the turmoil and impose another threefold increase in oil prices dealt a massive blow to the already fragile economies of the oil-importing developing nations. It also confirmed the prevailing pessimistic views on the future of oil.

A report to the government of Tanzania said:

> Tanzania must therefore assume that significant increases in imports of crude oil and products will not be available in future and that the unit costs of these imports will rise. This assumption has profound implications for industrial development, transport and all energy planning.[4]

The other major energy concern of the 1970s was fuelwood. In 1975, Erik Eckholm's Worldwatch paper *The Other Energy Crisis: Firewood*, suggested a parallel between the industrial world faced with vanishing oil resources and the Third World where the forests on which people depended for their energy needs were rapidly disappearing. High oil prices appeared to close off any escape from fuelwood shortages by Third World consumers switching to the use of kerosene for cooking. Mobilizing renewable energy resources and promoting the planting of trees for fuelwood[5] appeared to be the only feasible options open to the countries of the developing world without their own oil resources if they were to meet their future energy needs.

A CATALOGUE OF DISAPPOINTMENTS

The development assistance policies of the late 1970s and early 1980s reflected the energy concerns of their time. Providing substitutes for oil, especially in the rural areas, was seen as an urgent priority. The fact that renewables are, in general, environmentally more benign than fossil fuels added further weight to the case for their support.

Most of the development assistance agencies, therefore, devoted considerable attention to renewable energy sources. In some cases, separate departments or divisions were set up to deal exclusively with these technologies. In Germany, for example, a special agency, GATE (German Appropriate Technology Exchange), was established to promote new and renewables energy technologies. Even the World Bank appointed a Renewable Energy Advisor.

Particular support was given to NGOs as it was believed a decentralized locally-based approach would be the most effective method of promoting the use of energy sources which were themselves intrinsically decentralized. Much attention was also given to the dissemination of ideas. Numerous networks and newsletters were funded to promote renewables and disseminate information. Demonstration projects were supported; the Arusha Appropriate Technology Project in Tanzania, for example, had a variety of renewable energy devices on display and attracted hundreds of visitors per year, mostly from other countries.

The renewable technologies promoted included solar energy, small hydro, biomass gasification, biogas, wind power, residue briquetting and others. There is no necessity to go into details of these technologies as there is a copious technical literature describing them.

A comprehensive coverage is provided, for example, in Kristoferson and Bokalders[6] and a recent special issue of *Energy Policy* provided an up-to-date review of the main technologies.[7]

The most important fact in the present context is that the success ratio in all types of renewable energy projects over the past 15 years has now been low. Many did not work at all; the failure to develop effective long-term operation and maintenance systems meant that, of those which worked, few survived the departure of the foreign project staff who installed them; and the degree of spontaneous local replication was minimal.

In some cases, the impact of programmes was arguably negative. Instead of helping Third World countries with their energy problems, they induced governments to use scarce technical and managerial resources to establish renewable energy organizations with little real function or operational capacity. The renewable energy centre with its array of defunct and often highly implausible energy devices is, even still, a sadly familiar sight in many developing countries.

It would be pointless and depressing to attempt a full catalogue of these disappointments. The following review simply provides a brief sketch of what happened in the main technological areas.

Solar energy

The main focus of energy assistance in solar energy was on photovoltaics for water pumping and electricity generation. Most donor agencies promoted at least some activity in this area while large programmes were supported by France, Germany, Japan and the USA.

The number of technical failures in the early programmes was high. While the solar cells themselves proved, for the most part, reasonably durable, the ancillary equipment frequently failed under the harsh operating conditions of the rural Third World. The lack of spare parts and suitably skilled technicians meant that in many cases the equipment was simply abandoned. In recent years, the position has improved and there are now effective maintenance systems in a number of countries.

It is estimated that more than 2 000 solar pumps have been installed.[8] The average peak output is around 1 kW, making them primarily suitable for drinking water supplies. Perhaps 1 000 solar refrigerators have been installed, generally powered by photovoltaic units with a peak output of around 100 watts.

An unknown number of small lighting kits have been installed by aid agencies and private individuals; the total is probably in the tens of thousands. These are typically powered by panels with a peak output of 400–100 watts and are sufficient for a number of low-power fluorescent bulbs and a radio. The larger units are able to power a cassette player and a small TV set.

In spite of these successes, however, photovoltaic technology has so far failed to fulfil the expectations of its proponents. Most development assistance programmes have relied on the dissemination of highly subsidized equipment and there is little evidence that rural people are willing to repair or replace it out of their own resources when it breaks down. The degree of spontaneous take-up of the technology within the target groups has generally been negligible. One commentator within the solar energy community has written:

> The photovoltaic community must accept that the adoption of solar electric generation for development applications has been disappointing. Despite the obvious benefits, the take-up has been slow and sporadic. Really widespread use still looks as far away now as it was five years ago. It must be time to re-assess the situation and evaluate whether we misinterpreted the potential or merely failed to capitalise on it.[9]

Another question which has arisen concerns the longer term implications of supporting a wider dissemination of photovoltaic equipment. The power output of domestic lighting systems is not sufficient for the operation of domestic appliances such as hotplates, irons, or sewing machines, let alone equipment for grain milling or other commercial enterprises. The installation of photovoltaic lighting systems can thus block off access to these other electricity uses unless people are prepared to abandon their investment in the photovoltaic equipment. As one commentator has put it:

> First, the community can no longer expand demand to new processes, locations and applications at low marginal cost. The market cannot rationally increase or be allowed to increase beyond the volume indicated by the high marginal cost of a photovoltaic system. Second, the installation of photovoltaics has preempted classical development . . . The village is trapped at a subsistence level of electricity consumption.[10]

Photovoltaic systems nevertheless remain attractive for decentralized electricity production. The technology is well proven and solar energy is abundant and widely available. The challenge for development assistance is to find applications which are economically justifiable, socially appropriate, and technically sustainable.

At present, this means applications which are of high value, remote, low electricity demand and part of a network which can provide adequate repair and maintenance services. This is what has happened in the industrial world and provided a secure market for the already flourishing photovoltaic industry. There is no reason to suppose that the role for photovoltaics is, as yet, any different in the developing world.

Centralized solar power stations were built in perhaps half a dozen developing countries. These rely on a large array of photovoltaic panels with a total area of 100-200 square metres, mounted on a concrete plinth. In addition there is a control building with a battery storage room, a voltage regulation system, and a standby diesel generator. Power is taken to consumers by overhead lines or underground cables.

Typically, the total output is 10–15 kW and the cost $200 000–300 000. The station on Utirik Island in the Marshall Islands, for example, has an output of 8 kW and cost $280 000.[11] These stations have proven to be extremely unreliable and expensive to maintain; repairs frequently depend upon obtaining the service of expert technicians from the manufacturing company in the donor country. They are also highly inflexible and cannot be expanded to meet growing demand except at prohibitive costs.

There were also attempts to promote the use of flat plate solar collectors. The technology of these is well proven and they are sold commercially in countries such as Australia, Israel and the USA. As far as the developing world is concerned, their main potential is in the urban areas as their cost and technical complexity make them inappropriate in the rural areas, especially where there is no piped water supply. But efforts to promote their use have had little impact. Where significant numbers have been installed as, for example, in Gabarone in Botswana, there have been frequent problems of repair and maintenance which tend to be difficult to resolve because of the shortage of skilled plumbers and technicians.

Solar driers have generally turned out to be cumbersome and expensive and few projects have gone beyond the demonstration stage. The same is true of solar cookers. They have proved expensive, awkward and generally impracticable; there is now little serious interest in their promotion.

Small hydro projects

Small hydro was widely supported by a variety of donor agencies.[12] Projects ranged from relatively conventional installations in the megawatt range down to extremely small minimum-cost units in the 5-20 kW range. A number of excellent design manuals were produced and widely disseminated.[13]

The main success story appears to be Nepal where about 450 locally made water turbines have been substituted for the traditional wooden water mills used for milling grain; around 70 of these new turbines have been equipped with generators and provide power for lighting to the surrounding community in the evenings.[14] Elsewhere, the number of projects implemented under development assistance programmes appears to be small.

There have also been reports of technical, financial and managerial problems. A World Bank mission to the Philippines, for example, reported on a programme to develop 75 mini-hydro sites which was begun in 1980. By 1990, a total of 13 had been built but only four were operating satisfactorily. The other nine were facing problems of lack of water or site instability. In the Solomon Islands, resources have been expended on the identification of over 100 potential small hydro sites but only three have been developed, of which two are working satisfactorily.

A consensus seems to have emerged that entrusting small hydro to power utilities tends to be financially and managerially disastrous because of the huge diseconomies of scale. A study in India found, for example, that the operating costs of small hydro plants were nine times higher per kWh than those of larger hydro plant.[15] This is mainly because the design approach and standards used by utilities tackling small projects tend to be based on those for large projects; this brings large overheads in construction plant, access roads and site establishment costs. A power station with an output of 75 kW can be as expensive in these respects as one with an output a hundred times greater.

Taking small hydro out of the hands of the utility enables substantial cost savings to be made. The design can be matched to the actual needs of the local community rather than the mandatory national standards followed by the utility. Economies in construction can be obtained by using local labour and materials. Operating costs can also be cut substantially by having the plant operated by the local community. A number of such low-cost community-run hydro plants with outputs in the range 5-15kW have, for example, been installed in Pakistan under the auspices of the Pakistan Council for Appropriate Technology.

The main problem with such decentralized approaches tends to be the long-term management of installations. Small hydro plants are complex pieces of equipment. They cannot be installed and then forgotten. Experience shows that there are rarely sufficient local skills for long term operation, repair and maintenance. Unless there is a permanent central organization with the capacity and the funds to provide the necessary technical assistance as well as an effective maintenance and repair service, plants tend to fall into disuse.

It is, of course, possible to point to numerous successful small hydro installations. Mission stations, commerical farms, and a variety of small enterprises in different countries all have satisfactorily operating plants. But small hydro, like photovoltaics, has so far not fulfilled the expectations of its promoters in the development assistance field.

Biomass gasification and dendrothermal power

The production of producer gas from wood or charcoal, biomass gasification as it usually described, proved its technical feasibility and relevance during times of oil scarcity in Europe during the Second World War when over a million gasifiers were in use. The technology was revived after the 1973 oil price rise and numerous attempts were made by development assistance agencies to introduce it into the developing world.[16]

Projects were carried out in a wide variety of countries including Tanzania, Costa Rica, the Philippines, and a number of the Pacific island nations. There was also a spontaneous move by a number of private sector companies in Brazil to promote gasifiers in response to high petroleum prices.

While a certain number of privte sector gasifiers are reported to be still working in Brazil, the vast majority of development assistance projects failed on technical and economic grounds. Under the EEC-funded Pacific Regional Energy Programme, for example, a total of 17 gasifier projects were budgeted and approved throughout the Pacific island countries during the 1980s. A further 15 projects were launched in the same region under a variety of other funding arrangements during the same period. Of all these, only one, a 25 kW wood gasifier at a school in Vanuatu, is now working.[17]

In the Philippines, an apparently flourishing gasified programme which had been actively promoted by Imelda Marcos, was revealed to be deeply flawed after the collapse of the Marcos regime. The technical and economic weaknesses of the programme had apparently been concealed for political reasons and it has now collapsed completely.

One of the more surprising success stories is a Chinese-designed rice husk gasifier which has been working on the inland delta of the river Niger in Mali. Rice husk gasification is reckoned to be extremely difficult technically but this plant appears to have worked successfully since the mid-1970s. The design does not, however, appear to have been replicated elsewhere outside China.

The majority of commercial firms involved in gasifier manufacture appear to have abandoned the technology. A recent review states:

> The future of biomass gasification as a reliable energy alternative now hangs in the balance . . . no successful manufacturing has initiated from technical institutes . . . Without the expertise of responsible manufacturers to convert the theoretical knowledge of biomass gasification into usable equipment, there can be no future for the technology's reliable implementation.[18]

The only major dendrothermal programme was launched in the Philippines in 1980. Under this, fast growing trees, mainly *Leucaena leucocephela*, grown in special plantations were to be used as fuel for a series of small power stations. The original intention was that 17 power plants would be built. Of these, 13 had planned outputs of 3.2 MW and the remaining four were intended to have an output 1 MW each.

The programme was plagued with problems from the beginning. Almost a third of the 2 000 hectare plantations established to supply the wood had to be abandoned, and the yields of others were much lower than expected. Of the 17 projects, three were suspended during construction, five were suspended after the equipment was delivered, and three were abandoned at the planning stage. Six plants were finally built, of which three were in operation in 1990 and the programme had effectively been abandoned. The use of coal for firing the boilers was being investigated.

Biogas

The first large-scale biogas programme was launched by the Chinese government. Experiments were carried out in the 1950s, but the 1970s saw a remarkable dissemination of the technology. Some seven million digesters were reported to have been built, mainly in the warm and humid central province of Szechwan. One of the features of the Chinese experience, which was not widely appreciated elsewhere, was the extent to which it was based on long-standing traditions of fermenting sewage and animal dung in order to break the faecal pathogen cycle in areas where fish-farming and irrigated agriculture are carried out. Covering the digesters and utilizing the gas was a logical, though difficult and not always successful, next step.

The next largest programme is that in India where it was reported in 1985 that up to 280 000 had been installed, though other sources put the figure at about 80 000.[19] Development assistance projects to promote biogas were launched in a large number of other countries including Tanzania, India, Senegal, Central America, Vietnam and Thailand to take a random selection.

Biogas digesters can be divided into two broad types. The first is the Chinese which has a fixed brick-built dome. As a result, the pressure increases as the quantity of gas builds up inside the digester. One of the major problems with this type is its tendency to leak. Although reliable information on the Chinese programme is difficult to obtain, it is reported that a substantial proportion of the digesters are now out of action.

The other major type was developed in India. This uses a masonry digester with a floating steel cover which maintains a constant pressure. The main problem with the Indian digester has been the cost, which limits its use to the better off farmers. Difficulties have also been experienced with corrosion of the steel cover.

In general, biogas digestion has failed to make a significant impact outside China and India. The number of successfully implemented projects has been small and few have proved sustainable in the longer term. The degree of spontaneous local take-up of the technology has been negligible.

It is, at times, difficult to understand the degree of enthusiasm which biogas evokes. Digesters are costly and need to be built to high structural standards if leaks are to be avoided. The process is highly susceptible to changes in the ambient temperature and in the quality and quantity of the input materials. Considerable quantities of water need to be available if the plant is to be operated on a year-round basis; dry spells can also cause problems with cracking of structures.

A rough profile for areas in which biogas might be applicable would include a moist uniform climate; a regular supply of cattle dung and other feedstock; skilled labour for construction and maintenance; a reasonably affluent rural community; and a lack of alternative energy sources. Where these conditions were not fulfilled, the experience of the 1980s was that biogas technology did not succeed on a sustainable basis.

Other renewable energy technologies

Fermentation of biomass to produce ethanol is a well proven technology and it has frequently been advocated as a means of providing developing countries with the capacity to produce their own liquid fuel. The Brazilian programme is by far the largest and while it has undoubtedly succeeded at a technical level remains controversial on economic and social grounds.[20] The only other significant programme is in Zimbabwe. In both cases the ethanol is considerably more expensive than the gasoline it replaces. While sunk costs and political considerations may ensure the survival of these programmes, few would advocate their replication in other developing countries at present.

Programmes to introduce windpower for irrigation pumping have had a limited amount of success in a number of countries. Stand-alone electricity generation has, however, tended to be unreliable and expensive and has been almost entirely confined to isolated 'demonstration' projects. The commercially successful use of wind generators for grid supplies in the USA, Denmark and elsewhere has, however, evoked interest in some developing countries. A programme to support the manufacture of wind generators in India is, for example, being supported by the Danish development assistance agency Danida. But there is still a significant amount of debate as to whether wind-generated electricity is truly an economically competitive option.

Other renewable energy technologies which have been promoted or suggested include residue briquetting, small steam engines, wind-diesel systems, wave-power, biomas fuelled sterling engines and, even, ocean thermal gradient power. Although a variety of isolated projects have been completed in the developing world, the impact has been small and the immediate prospects look to be limited.

UNDERSTANDING WHAT WENT WRONG

It is easy to see with the benefit of hindsight what went wrong with the renewable energy assistance of the past 15 years. But the purpose in doing so is not to score cheap points. It is to see if it is possible to learn some useful lessons from the experience so as to prepare a more secure foundation for the energy assistance policies of the future.[21]

Technical and maintenance problems

Large numbers of projects encountered major technical problems. The special status enjoyed by renewables, as ecologically benign substitutes for petroleum, paradoxically, worked very much to their detriment. It meant that many renewable energy projects were exempt from normal engineering scrutiny. The fact that they did not use petroleum fuel was, in itself, frequently taken as sufficient justification for their implementation.

The result of this lack of adequate technical screening was that a large number of technically unsound or immature projects were initiated. Biomass gasifiers which did not work to any acceptable degree of reliability were set up in various places. Solar cookers which could not be used for cooking, biogas digesters which did not digest, solar water heaters which could not hold water, and a host of other devices which were poorly designed or ill-suited for their working context were implanted in the developing world by aid programmes.

Many projects were, in fact, little more than technical research exercises masquerading as energy assistance. But instead of this research being carried out in well-equipped workshops and laboratories it was taking place under the extraordinarily adverse conditions of isolated Third World villages. The reliance on enthusiastic but technically unsophisticated NGOs for the implementation of many projects added to the problems. It was little wonder that so many failed to achieve their objectives.

Nor, in most cases, was sufficient attention paid to the problem of long-term maintenance. Local people rarely have the necessary technical skills even for routine maintenance and cannot be expected to diagnose faults and carry out repairs on unfamiliar technical devices. Unless there is a critical mass of installations, which can provide the justification for a self-sustaining local repair and maintenance system, experience has amply demonstrated that installations will fall into disuse.

Photovoltaic installations, which were heavily promoted on the basis of their low maintenance requirements are a particular case in point. It is undoubtedly true that they are considerably simpler to maintain than diesel generators, but is also absolutely essential that they are looked after properly. One of the most critical elements in these systems, for example, turned out to be the battery. Excessive charging and discharging, or neglecting to top up with distilled water can bring about rapid failure. Where car batteries are used, as is frequently the case, instead of the more expensive types designed for frequent deep charge and discharge cycles, the life is likely to be only a year or so.[22]

Component failures, even though relatively rare, can also be a major problem as stocks of spare parts and technicians with the necessary skills are rare in the developing world. Unless there is a reliable maintenance system, backed up by a repair service with adequate spare part stocks, experience shows that systems quickly go out of use.

High costs

The other major problem of renewables in development assistance has been cost. The fact that installations tend to be small and isolated adds to the problem since the overheads, especially of foreign consultants and contractors, tend to be extremely high.

In the case of small hydro, figures of \$5 000/kWh and higher have been quoted for a variety of projects. The 1 MW scheme in Cuamba in northern Mozambique, to take an extreme example, had a cost of \$12 000 per installed kW and a firm capacity of 350 kW.

Run-of-the-river schemes are considerably cheaper but at the expense of a considerable loss in flexibility. Since there is no water storage, the power supply depends entirely upon the flow in the river. Unless this happens to coincide closely with the local demand pattern, the lack of power when it is required is likely to result in a build up of local frustration and dissatisfaction with the system.

Cost is also a major problem with photovoltaic systems. While it is true that the price of solar cells has continued to fall since their introduction in the 1950s, they are still in the region of \$5 per peak watt.

It must also be borne in mind that the cells are only part of the total cost of a photovoltaic installation. The 'balance of system costs', for the mounting, wires, switches, batteries, ballasts, control systems, special low power lights, refrigerators and other equipment, which can make up 50% or more of the total cost of an installation, are not susceptible to the same cost reductions. These are often not given the attention they deserve:

> The other components of a solar home system (SHS) are more decisive for the economics of the system than the solar panel itself – something many people still do not seem to realise . . . Indeed, some solar equipment manufacturers and proponents of the SHS option feel that emphasising the possibility of future declines in the cost of solar modules and using cheap charge-regulators and primitive ballasts they can make SHSs commercially viable. However, there is a real danger that a strategy of this type will have just the opposite effect.[23]

The overall result is that photovoltaic systems are still extremely expensive in comparison with conventional alternatives. Lighting kits with a peak output of 50 watts, for example, are commercially available at prices of \$750–1 500 depending on size and location. For comparison, small petrol generators with an output of 0.5 kW, roughly ten times that of the photovoltaic system, tend to be available at around \$750. Solar refrigerators tend to have installed costs in the range \$3 000–6 000 whereas a comparable unit powered by kerosene costs about one-tenth as much. A solar pump with an output of 1.25kW tends to cost around \$25 000, again far more expensive than the diesel alternative.

Unjustified pessimism about oil

Perhaps the most important factor inhibiting the growth of renewables has, however, been the fact that oil prices have failed to rise as predicted. The common belief in the 1970s that oil resources were on the verge of depletion was, of course, always mistaken. It was a result of a popular misunderstanding of what a number of analysts had been saying about trends in oil consumption.

The concern of these analysts was not that oil resources would have completely vanished by the year 2000 but that the growth in oil consumption, which had run at around 7.5%/year through the 1950s and 1960s, could not continue to do so for very much longer. Analyses based on estimates of the total amount of oil likely to be recoverable showed that consumption could continue to increase up to about the turn of the century, when it would be double the 1970 level, but would thereafter begin to decline.[24] The date of this peak in consumption was popularly misinterpreted as the time at which oil would no longer be available.

In the event, growth in oil consumption virtually ceased in the early 1970s. The total increase between 1973 and 1989 was 7.3% and between 1979 and 1989 there was no growth. Fears of imminent depletion were also shown to be unfounded. Figures for 'published proven' oil reserves over the period 1970 to 1989 increased by 64% from 84 billion tonnes to 138 billion tonnes; that is 45 years' production at present levels. No one doubts that there is a great deal more oil left to be discovered which will extend the life of reserves considerably further.

There are also the unconventional sources of oil to be exploited. Development work is being carried out, for example, in the Orinoco heavy oil belt in Venezuela. These reserves can be recovered, transported and used in boilers in the form of an oil-water emulsion known as Orimulsion. A number of pilot projects have been launched and production costs are about $3/bbl. It is estimated that there are recoverable reserves of about 40 billion tonnes.[25]

Similarly, the worries about steadily rising prices proved unjustified. The increases imposed in 1979 turned out to be unsustainable. When the price of Arabian light crude oil dropped to $13 per tonne in 1988, it was back, in real terms, to about 50% of the price set by OPEC after the 1973 Middle East war. More recently, initial fears about the Gulf War pushed prices up to $35/bbl but they soon fell back to around $20/bbl despite the complete loss of production from Iraq and Kuwait. One of major problems facing OPEC will be to prevent its own disintegration and a collapse of the oil price to $10–12/bbl when production from these two countries is fully resumed.

Prior to the Gulf crisis, the medium term equilibrium price for crude oil appeared to be around $18/bbl.[26] The ability of world markets to cope with the loss of production from Iraq and Kuwait suggests that, if anything, this estimate may be too high. On present evidence, there is no reason to suppose there will be any major increase in oil prices, in real terms, before the end of the 1990s. It leaves oil, as it was throughout the middle and late 1980s, the cheapest energy for the majority of Third World end uses apart from domestic cooking.

The economic conditions under which renewables were expected to be economically competitive have thus not materialized. While it is true that wind power has been a commercially viable investment in some countries over the past decade, it has been the beneficiary of a variety of tax incentives and governmental promotional schemes, leaving the question of its viability under market conditions still open to debate. Similarly the apparent commercial success of large-scale thermal solar plants in southern California[27] has been undermined by the recent failure of the main promoting company Luz International. In short, the clear demonstration of market competitiveness which would stimulate a significant and spontaneous flow of investment capital into renewables remains as elusive as ever.

RENEWABLES IN THE ENERGY ASSISTANCE OF THE 1990s

There is no question that secure energy supplies remain a vital necessity for all Third World countries. Energy assistance will therefore continue to fill a need, especially in the poorer developing countries. Rising worries about global warming have created additional pressure for the deployment of renewables. But the role which they can, or should, play in development assistance remains open to debate.

Clarifying objectives

In looking at the potential role of renewables, it is essential to bear in mind the primary objective of development assistance. It is to promote economic growth in the developing world.

The first essential, therefore, is that the economic benefits from the use of an energy source should exceed its costs. If the economic return from the project is less than the economic costs, then rather than promoting development, what has actually been created is a development sink. The common argument that renewable energy projects can be exempt from this requirement because it is donor rather than local money which is being spent is not valid. It presupposes that there is no other use for the same money. It also leaves developing countries in a technical dead-end, carrying the long term operation and maintenance costs of projects which they cannot afford to renew or replicate.

It follows that objectives such as 'promoting the wider dissemination of renewables' need to be treated with some suspicion in a development assistance context. It is, of course, perfectly reasonable to aim for the wider use of renewables, but this is not necessarily, or even often, the same as providing developing countries with the most appropriate solution to their energy needs. Renewables should only be used when they provide the technically and economically optimal solution.

Caution is also needed in the use of supplementary funds from an environmental budget, such as the Global Environmental Facility, to top up the extra costs of renewable projects on the grounds that they do not produce greenhouse gases. It cannot be automatically assumed that because a renewable energy source does not emit carbon dioxide it is the best use of these funds. It might, for example, make far more sense to use the same money to improve the efficiency of a local thermal power-plant.

Nor, in looking at global environmental issues such as atmospheric warming, should the developing nations be asked to bear a heavier burden than the industrial world. The main responsibility for the global warming problem lies with the industrial world and Third World countries should not be asked to base their development on energy sources which the industrial world itself does not believe are economically competitive or technically mature.

Need for greater rigour in economic and technical analysis

Ensuring that such criteria are applied in future development assistance in the energy area will require a considerably greater rigour in the economic and technical analysis of renewable energy sources than was shown in the 1980s.

As a broad rule, projects should provide a minimum economic internal rate of return (IRR) of around 10%. This should obviously not be used as an inflexible criterion for all projects. But a low IRR should always be regarded as a strong warning signal and an indicator that the project has poor development-creating potential.

In addition, the renewable option, if it is to be adopted, should provide the least-cost solution. If this is not done, the economic benefits from the project are going to be less than they might be. There may be grounds for flexibility in the assessment of costs and benefits – a renewable energy project may, for example, provide additional local employment – but there can be little justification for deliberately imposing economically sub-optimal solutions on impoverished local communities.

Flexibility is another important consideration. People's needs and aspirations change with time. A small photovoltaic or microhydro system which meets the minimum electricity demand may turn out to be inadequate to meet expanding demand long before the end of its working life. The costs and technical problems involved in expanding the system should be analysed at the outset and a practical way forward should be identified. Otherwise there is a danger that, after the initial benefits have been provided, the project may effectively act as a block on further development.

The same hard-headedness must be used in the detailed technical evaluation of projects. There is no point in providing the developing world with technology which does not work satisfactorily in the conditions for which it is intended. The technology which is used in technical assistance programmes must therefore be adequately proven for the task it is to fulfil. In general, it should be commercially available, off-the-shelf, and covered by normal manufacturers guarantees.

Similar attention must be given to the question of sustainability; unless projects are sustainable, they cannot contribute to the long-term economic development of the countries in which they are implemented. Installing isolated pieces of equipment and hoping that local people will keep them in action is a certain recipe for failure. There must be a sufficient number of local uses, who are willing to pay the necessary costs, to support a local repair and maintenance service. The financial and institutional issues which this raises are often far more critical to the success of projects than the technical choices on which the greater attention often tends to be focused.

Another important issue is that of local replicability. There is little developmental benefit in an initiative which helps a single village or family but which the recipient country cannot apply elsewhere. From the beginning, projects should aim at being replicable on a significant scale and with decreasing reliance on assistance from abroad.

CONCLUSION

In the long-term perspective, renewable energy sources and, indeed, nuclear power appear essential. No other energy scenario seems plausible given the environmental and resource constraints on fossil fuel consumption and the likelihood of a doubling of the human population. In such an energy future, the present developing world would, no doubt, obtain a similar proportion of its energy needs from renewables as the industrial countries.

But such a future will require a considerable amount of investment in research, development and infrastructural change. As a recent review puts it:

> The more we want renewable energy technologies (RETs) to be a reality, the more changes are needed in current energy policies, infrastructure, institutions and attitudes. There are no shortcuts or simple answers and it is important to realise that RETs will ways be controversial. Their

contributions will be limited in many sectors, they will require additional development, sometimes up-front funding will be required. . . . The cutting edge of RET development will have to be in the industrial contries, particularly in the IEA countries. If nothing happens there, nothing will happen at all.[28]

In the majority of developing countries, the urgent needs of the present moment have first priority. Economic development is essential for social and political reasons and is a precondition of population stability and the protection of the natural environment from the expansion of low-intensity subsistence farming. If this economic growth is to be achieved as rapidly as possible, the energy sources used need to be technially mature and the most cost-effective available.

Renewables can certainly be part of the solution provided they meet the necessary technical and economic criteria; this is the challenge facing those who wish to see them more widely used. But if they are deployed without meeting these criteria, they become part of the problem of underdevelopment.

This paper relies on a presentation at a seminar in the Stockholm Environment Institute in April 1991 and subsequently published under the title *Energy Assistance Revisited*. Thanks are due to the Stockholm Environment Institute for funding the study and especially to Lars Kristoferson and Sven Hunhammer for their help and support.

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[3]T.B. Johansson and P. Steen, 'Solar Sweden – an outline to a renewable energy system', Secretariat for Future Studies, Stockholm, 1977.
[4]IIED, *Energy Policy in Tanzania: Report to the Government of the United Republic of Tanzania*, International Institute for Environment and Development, London, UK, 1980. The quoted paragraph was, incidentally, drafted by the present author who was a member of the study team; those who use hindsight to point out where others were wrong should not exempt themselves from its unforgiving scrutiny.
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Part IV: Strategies for Implementation

Chapter 16

Policies for a Solar Economy

Chris Flavin and Nicholas Lenssen

Punctuated by oil shocks and ultimately limited by environmental concerns, the fossil-fuel age may be nearing its close. While the renewable technologies are now available to make the transition away from today's coal- and oil-based energy system, existing energy policies do little to accelerate the commercial development of renewable energy. This paper examines some of the policy reforms needed to make the transition to a renewable energy economy, beginning with a change in energy pricing that internalizes the environmental and security costs of fossil fuels. Utility reform, a major shift in current energy research and development spending, and the creation of an international renewable energy agency are among the key elements of a sound energy policy that will allow the 60–80% reduction in carbon emissions needed to stabilize atmospheric CO_2 concentrations.

Keywords: Solar energy; Energy policy; Renewables

The end of the fossil fuel age is now in sight. As the world lurches from one energy crisis to another, dependence on oil and coal threatens to derail the global economy or disrupt its environmental support systems. If we are to ensure a prosperous world for future generations, only a few decades remain to shift the world economy to reliance on renewable resources.

Fortunately, the technologies are at hand to begin the transition away from fossil fuels. What is missing is a focused effort on the part of governments to provide the policy framework that can accelerate the commercial development of renewables.

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Three oil shocks in 17 years are sufficient warning that the world cannot continue indefinitely along a path of petroleum dependence. The ultimate constraint is physical – oil supplies are finite – but the immediate limits are geographical and political: nearly two-thirds of the world's proven oil reserves are in the volatile Persian Gulf region. Outside the Middle East, much of the cheap oil has already been consumed.[1]

An even more fundamental limit on fossil fuel use is the atmosphere's capacity to cope with the burden of nearly 6 billion tonnes of carbon emissions each year. Scientists working with the United Nations-commissioned Intergovernmental Panel on Climate Change predict that these emissions will warm the atmosphere at an unprecedented rate, and may eventually undermine the economy itself.

Combustion of all the world's remaining fossil fuels would raise the concentration of CO_2 as much as tenfold, compared with the mere doubling that now concerns scientists. Stabilizing the climate will require reducing global CO_2 emissions by 60 to 80%; slowing global warming inevitably means placing limits on fossil fuel combustion.[2]

Just as environmental concerns have surged, the commercial readiness of renewable energy technologies has advanced. Unlike the 1970s, when efforts to promote renewable energy were undermined by the lack of a technological base, policymakers today have many strengths to build on.

In the USA, for example, some 15 000 privately-owned wind turbines generate $200 million worth of electricity annually – enough to power all the homes in San Francisco. Commercial geothermal power plants are being built in a host of countries, principally around the Pacific 'Rim of Fire'. The market for photovoltaics is bursting at the seams: 50MW worth of solar cells were produced in 1990; continuing growth of 20 to 30% annually is likely as rural Third World use continues to gather momentum.

Table 1. Costs of renewable electricity, 1980–2030.[a]

Technology	1980 (1988¢/kWh)	1988	2000	2030
Wind	32[b]	8	5	3
Geothermal	4	4	4	3
Photovoltaic	339	30	10	4
Solar thermal trough with				
gas assistance	24[c]	8[d]	6[e]	8[f]
parabolic/central receiver	85[g]	16	8	5
Biomass[h]	5	5	–	–

Notes: [a]All costs are levelized over the expected life of the technology and are rounded; projected costs assume return to high government R&D levels: [b]1981; [c]1984; [d]1989; [e]1994; [f]estimates for 2030 have not been determined, primarily due to uncertainty in natural gas prices. [g]1982; [h]future changes in biomass costs are dependent on feedstock cost.
Source: Worldwatch Institute, based on Idaho National Engineering Laboratory *et al*, *The Potential of Renewable Energy: An Interlaboratory White Paper*, prepared for the Office of Policy, Planning and Analysis, US Department of Energy, in support of the National Energy Strategy (Solar Energy Research Institute, Golden, CO US, 1990), and other sources listed in Ref 4.

It is time for energy policy to re-focus on the longer-term, on how to promote the kind of energy economy we will need to achieve in the next few decades. The broadest challenge is to encourage investment and innovation in dozens of key technologies including: improved batteries; photovoltaics; more efficient engines; fuel cells; and, hydrogen storage systems. Tax code changes, electric utility reforms, revitalized R&D programmes, strengthened local government policies, and new international initiatives all have important roles to play.

A NEW START FOR ENERGY POLICY

Imagine an energy system that requires no oil, is immune to political events in the Middle East, produces virtually no air pollution, does not generate nuclear waste, and yet is just as economical and versatile as today's energy economy. Does this sound like a utopian dream? Hardly. Scientific and engineering breakthroughs now make it practical to begin producing our electricity, heating our homes, and fueling our cars with renewable energy – the energy of the sun, the winds, falling water, and the heat within the earth itself.

The conventional wisdom among government leaders, energy experts, and the public at large is that we are stuck with today's fossil fuels – whatever the cost in future oil crisis, air pollution or even a disrupted world climate. But, with continuing advances in technology and efficiency improvements that make it possible to run the economy on ever decreasing amounts of power, a renewables-based economy is likely to be achieved within a few decades.

Steady progress has been made since the mid-1970s in a broad array of new energy technologies that will be needed if the world is to increase its reliance on renewable resources. The step of harnessing renewable energy has been slow in coming because of technological lag-times, government neglect, and the 70% decline in oil prices between 1980 and 1986.[3]

Over the past decade, the cost of solar thermal power has fallen 66%, wind power 75%, and photovoltaic electricity 90% (see Table 1). Many of the machines and processes that could provide energy in a solar economy are now almost economically competitive with fossil fuels, and rapid commercial development of several of these technologies is expected during the next decade, driven not only by technical advances but by world oil and climate trends.[4]

In California, the future has already begun to emerge. The State that always seems to be a decade ahead of everyone else is once again ushering in a new era that is evident in the wind-driven turbines east of San Francisco, and the solar troughs in the Mojave Desert. Since the early 1980s, California has stopped building coal and nuclear power plants, and has turned to renewable energy. The State now gets 42% of its electricity from renewable resources, largely from hydropower, but also from geothermal, biomass, wind and solar energy developed in the past decade.[5]

But for all its success, California's energy revolution is a bit one-dimensional: its electricity system has been altered, but its cars and homes are still fueled largely with fossil fuels. The next step is to find a way to run the whole economy on intermittent renewable energy sources.

One missing link is hydrogen – a clean-burning fuel easily produced using renewable power and conveyed by pipeline to cities and industries thousands of miles away. Hydrogen shows great promise as the new 'currency' of a solar economy. It can be used to heat homes, cook food, power factories, and run automobiles. Moreover, the technologies to produce, move, and use hydrogen are already here in prototype form. The challenge of creating a clean, efficient, solar-powered economy is essentially that of reducing the cost of the various constituents of a solar-hydrogen system – from the manufacturing costs of wind turbines to the efficiency of new automobiles.[6]

The main political challenge is to overcome narrow economic interests, and revamp policies to create sustainable energy systems. The transformation of energy institutions will take many years to accomplish, but is likely to accelerate as policymakers awaken to the environmental and economic challenges they face.

A POLICY AGENDA

Since the mid-1970s, many nations have sought to redirect their energy policies to reduce dependence on oil. While these efforts did yield results, by 1990 oil demand was nearing the levels of the late-1970s, and non-OPEC production was falling steeply – in the USSR, North America, and the UK section of the North Sea. Many oil analysts believe that the world will become vulnerable to social or political upheavals in the volatile Middle East by the late-1990s. This has encouraged a number of countries, notably Japan, to reinvigorate their efforts to reduce oil dependence.

Since 1988, the world has begun to consider more fundamental energy policy changes, focusing on limits to CO_2 emissions. Some 23 countries have established goals, ranging from freezing emissions at current levels to cutting them by 50% (see Table 2).[7] At the Second World Climate Conference, held in Geneva in November 1990, 137 nations agreed to draft a treaty by 1992 to slow global warming.[8]

While the treaty details remain to be determined, the world appears headed to a commitment to energy systems less dependent on fossil fuels. Plans to stabilize the climate are likely to focus on improving energy efficiency and developing renewable sources of energy. Many nations are making progress on energy efficiency, but renewable energy continues to lag. It is therefore time to launch a renewable energy policy agenda.

Today's energy policies are often biased against solar energy. Carl Weinberg, director of research and development at the Pacific Gas and Electric Company, and Robert Williams, senior research physicist at Princeton University's Center for Energy and Environmental Studies, note: 'The rules of the present energy economy were established to favor systems now in place'.[9]

Most of these rules were created decades ago, when the central issue was how to expand fossil-fuel use rapidly. Hastening the transition to a sustainable energy economy requires a major shift in priorities – a shift that existing institutions and industries may find threatening.

While needed policy changes number in the hundreds, this article focuses on five priorities: reducing subsidies for fossil fuels and raising their taxes to reflect security and environmental costs; reforming the electric utility industry; strengthening state and local energy policies; increasing R&D on efficiency and renewable energy technologies; and, reordering the priorities and programmes of international institutions.

Energy subsidies, prices and taxes

Energy price reform is a prerequisite to the accelerated use of renewable energy technologies. Today, governments routinely provide subsidies to traditional energy sources, keeping prices artificially low and encouraging energy waste. As these policies are changed and environmental externalities are internalized, renewable energy will become more competitive.

Market reforms in once centrally planned countries may provoke the largest changes. In China, for example, coal costs about one-quarter the world market price, and in the USSR, oil was traded among state companies for less than $1/bbl in 1990. The price of Soviet oil, for example, was scheduled to triple in 1991.[10]

In the industrial market economy countries, smaller but still pernicious subsidies exist. Energy industries in the USA received Federal subsidies worth more than $44 billion in 1984 (the most recent data available). President Bush's successful 1990 effort to gain $2.5 billion in additional tax breaks for the US oil and gas industry is a recent example of the special treatment still received by specific, entrenched industries.[11]

As subsidies are removed, governments can also take steps to ensure that fossil fuel prices reflect

Table 2. National climate policies, proposed or enacted, October 1990.

Nation	Goal	Status
Australia	Reduce greenhouse gas emissions 20% from 1988 level by 2005	Commission is studying cost-effective measures
Austria	Reduce CO_2 emissions 20% by 2005	Commission to study policy options, including improved efficiency
Canada	Freeze CO_2 emissions at 1990 level by 2000	Task force to report recommended policies in November 1990
Denmark	Reduce CO_2 emissions 20% by 2005, 50% by 2020–2040	Energy plan approved with focus on efficiency, renewables, natural gas, energy taxes and transportation
France	Freeze CO_2 emissions near 1990 per capita level	No specific policies announced
Germany[a]	Reduce CO_2 emissions 25% from 1987 level by 2005	Action plan presented in November 1990; to include energy policy reforms and possible carbon tax
Japan	Freeze CO_2 emissions at 1990 level by 2000	Programme announced that includes efficiency, transport, nuclear energy, and renewables
Netherlands	Freeze CO_2 emissions at 1990 level by 1995, followed by reduction	Plan adopted that includes efficiency, renewables, natural gas, carbon tax and transportation reforms
New Zealand	Reduce CO_2 emissions 20% by 2005	Government agencies are developing policies
Norway	Freeze CO_2 emissions at 1989 level by 2000	Commission to recommend new policies in January 1991
Sweden	Freeze CO_2 emissions at 1988 level by 2000	Carbon tax will start in January 1991; parliament debating further policies
Switzerland	Reduce CO_2 emissions 10% by 2000	Programme announced for carbon tax, efficiency, and transport reform
UK	Freeze CO_2 emissions at 1990 level by 2005	Government paper calls for efficiency, renewables, and transport reforms

[a] German goal is for the former West Germany. Reduction goals for the former East Germany are being assessed.
Source: Worldwatch Institute, based on sources listed in Ref 7.

their full security and environmental price tag. The cost of developing armed forces in the Persian Gulf, for example, is not now being paid by consumers of Middle Eastern oil. Counting the cost of US preparations for war in the region, even before the 1990 troop deployment, for example, would add more than $60 to each barrel of oil imported into the country, according to Alan Tonelson and Andrew Hurd of the Economics Strategy Institute.[12]

Fossil fuel burning is exacting an even larger cost on the health of people and ecosystems around the globe. In the USA, for example, air pollution is estimated to add more than $40 billion to annual medical bills, according to the American Lung Association. Including such costs in the price of energy would allow markets to more accurately determine the least expensive means of meeting energy needs. Governments could do this by taxing energy to incorporate environmental costs into the price paid by consumers.[13]

A 1990 study by researchers at Pace University, in White Plains, New York, reviewed various estimates of the environmental costs of electricity technologies. The study found that electricity from coal would need to be priced at least 100% higher to cover its environmental costs, chiefly those resulting from air pollution-related damage. Oil-generated electricity would need to rise at least 50%, and natural gas much less.[14]

In the USA 17 States are already incorporating environmental costs in their regulation of electric utilities, though still at levels below those that might

Table 3. Gasoline prices and taxes, selected countries, October 1990.

Nation	Price (including tax) ($/gallon)	Tax	Equivalent carbon tax[a] ($/tonne of carbon)
USA	1.32	.30	121
Japan	3.44	1.44	575
Germany	3.52	1.97	787
UK	3.71	2.08	833
France	4.32	2.95	1 181
Italy	5.19	3.56	1 423

Notes: [a]Current gasoline taxes translated into a levy on the carbon content of fuel.
Sources: Karen Treanton, Statistics Department, International Energy Agency, Paris, private communication and printout, 2 November 1990; Carbon content of gasoline from Gregg Marland, 'Carbon dioxide emission rates for conventional and synthetic fuels', *Energy*, Vol 8, No 12, 1983.

be justified. European countries are also beginning to account for the costs of pollution, primarily through increased taxes. Sweden, for example, proposed taxing sulphur and nitrogen oxide emissions in April 1990; the following month, France levied a tax on sulphur dioxide. Italy started taxing low-sulphur fuels at half the rate of high-sulphur fuels in July 1990.[15]

Energy taxes are another tool for encouraging the use of renewable energy. Most countries already tax energy, though the levels vary widely. The most popular energy tax is on gasoline. In Europe and Japan, gasoline taxes in October 1990 ranged from $1.44 to $3.56/gallon, resulting in total retail prices of $4 to $5/gallon in some countries (see Table 3). And in 1991, several European countries raised gasoline prices substantially.

In the USA, however, the combined Federal and State tax averaged just ¢30/gallon, though it rose modestly to ¢35/gallon in December 1990. The inability of the USA to levy a higher gasoline tax is both a stimulus for the country's energy waste and a contributor to its huge Federal budget deficit.[16]

Another way of reflecting environmental costs is a broader energy tax or one that is specifically linked to emissions of CO_2. The latter tax would directly incorporate the anticipated costs of global warming in the prices paid for energy. Under such a levy, coal would be taxed the heaviest, since it releases the most CO_2 when burned, followed by oil, and finally natural gas. Nuclear power and renewable energy sources, which do not release CO_2 directly, would go untaxed. However, a general energy tax, the approach favoured by many Europeans, would tax nuclear power and renewable energy, removing the advantage for renewable energy.

Carbon taxes are fast becoming a reality in Europe. Both Finland and the Netherlands introduced such a tax in 1990, and Sweden and Norway levied them in January 1991. Germany, Japan, Switzerland, and the European Community as a whole are also weighing carbon taxes. While most of the taxes proposed so far are relatively small, a larger tax of at least $100/tonne of carbon would be needed to significantly affect energy trends. While this may seem like a large sum, most countries already tax gasoline at an effective rate of more than $100/tonne. Indeed, Italy's current gasoline tax is equivalent to a carbon tax of more than $1 400/tonne.[17]

Some analysts argue that energy taxes will lead to economic chaos, noting that higher energy prices in 1973 and 1979 had a devastating effect. But as Harvard University economist Dale Jorgenson has shown, two-thirds of the economic slowdown after the oil shocks of the 1970s was caused by the speed of the energy price increases. If price rises are gradual, as planned in most carbon tax proposals, the threat of an energy-price-induced recession can be removed. Indeed, European countries and Japan already have energy taxes far greater than those in the USA, yet their economies are, if anything, stronger.[18]

One energy model examined by the US Congressional Budget Office found that a phased-in $110/tonne carbon tax would reduce carbon emissions 27% from 1988 levels by the year 2000, and reduce the country's economic output that year by less than 1%. Another analysis, by William Chandler of Pacific Northwest Laboratories, concluded that a $94/tonne carbon tax would hold carbon emissions at today's level by the year 2000. Such a tax could actually boost economic output if it were used to offset other taxes.[19]

Utility reform

Changing energy prices will not remove all the barriers to development of renewable energy,

Table 4. Electric utility reform, selected countries, October 1990.

Nation	Description of action
Brazil	Independent power producers permitted to connect to electricity grid
Costa Rica	Utilities required to pay competitive prices to independent power producers
Denmark	Utilities required to purchase power from independent renewable power producers and district heating plants
Dominican Republic	Utilities required to pay competitive prices to independent power producers
Germany	Independent power generation being encouraged; competitive prices paid to renewable energy producers
Norway	Utility reform approved, aimed at increasing competition in electricity generation
Pakistan	Incentives offered for independent power producers
Portugal	Power plant construction and ownership being shifted to private companies; independent power producers, including renewables, emerging
Thailand	Limited sale of state-owned utility planned; incentives for cogeneration and biomass producers
UK	State-owned utility broken up and sold to private investors; independent producers emerging
USA	Reforms by individual States including competitive bidding, integrated resource management, and incentives for efficiency investments

Source: Worldwatch Institute, based on sources listed in Ref 21.

however. Basic reforms of energy institutions and industries are a second priority – particularly the publicly-owned or regulated electric utilities.

These companies were set up to create large electric power systems from scratch. As a result of their efforts, electricity now represents roughly one-third of the world's primary energy supply. Whether privately-owned, as in the USA, or state-owned, as in France and India, these utility monopolies are now anachronistic. At a time when the world needs to use electricity more efficiently and develop new and cleaner ways to generate power, major reforms are in order.[20]

Since the early 1980s, a growing number of countries have begun to rebuild their electric utility systems in a more flexible, decentralized, and competitive mold. These reforms have ranged from the encouragement of an independent power industry in Costa Rica to the sale of the national electric power system to private investors in the UK. Pakistan and Portugal are allowing private companies to build their own plants and sell power to the utilities, while Norway is stripping its powerful national utility company of its monopoly status (see Table 4). No country has completed the process of utility reform, and most have a long way to go.[21]

The broadest efforts at such reform are found in the USA, where diverse State-by-State efforts have been underway since the passage of the Federal Public Utility Reform and Policies Act (PURPA) of 1978. In California, for example, State regulators have required the privately owned companies that provide most of California's electricity to invest in energy efficiency, not just power plants. The resulting efficiency improvements will make it easier for California to make the transition to renewable energy.

As a result of these efforts, per capita use of electricity in the State fell slightly between 1978 and 1988, compared with an 11% rise in the rest of the USA. California eliminated the need for $10 billion worth of new power plants and reduced electricity consumption per dollar of gross State product by 17%.[22]

California officials expect future gains to exceed those of the past. In August 1990, the State's four largest utilities agreed to spend $500 million over two years on improved energy efficiency; State regulators will ensure that the utilities profit from these investments, more than compensating them for the lost revenues from reduced electricity sales. New York, Oregon, and five New England States now have similar programmes. Utilities are gradually being converted from energy producers to energy service companies, and the California Energy Commission believes this change may soon stop or reverse the growth of electricity demand.[23]

Since the early 1980s, California has also required utilities to purchase power from qualifying private companies – many of them relying on renewable power sources. In just a decade, the State has developed a thriving renewable electricity system. In 1990, 12% of the State's electricity was expected to come from alternatives such as geothermal, solar, wind, and biomass. By encouraging energy sources that are inflation- and embargo-proof, California demonstrated that with the right policies, energy transitions need not be long, painful affairs.[24]

Today, California and several other States are working on new policies to encourage more independent power development at the lowest possible cost. The key is to create a bidding system that allows companies to compete against each other for the right to produce power – the kind of competition that exists in any market. While devising bidding rules is complex, these rules are crucial to the pace of development of new energy systems.

So far, most governments have been slow to open their power industries to competition. Some companies have been sold to private investors but retain their monopoly status, while in nations such as Germany, only small renewable producers are permitted to join the competitive power market. This slow progress reflects the political strength of utilities, and scepticism about the reliability of a redesigned power industry. But experience now shows that, while power transmission and distribution need to be a regulated monopoly, the generation business works better as a competitive, market-regulated enterprise. The main role of utility companies in the decades ahead may be on the demand-side – providing the capital and expertise needed to improve energy efficiency and to install household solar systems.[25]

Local government responses

Local governments can also play a role in re-shaping our energy future. They are best equipped to encourage energy savings in housing, transportation, and land use planning. And since renewable sources of energy are by nature decentralized, local governments are well positioned to support them.

Transportation and buildings together account for nearly two-thirds of all the energy consumed in industrial countries. Building codes recently have been modified in many areas to include tougher energy standards for new construction. In most regions, standards need to be tightened and energy consumption in existing buildings cut through weatherization programmes.[26]

A sustainable transportation system can only be created with policies that reduce reliance on automobiles and encourage a switch to public transport, biking, and walking. Restricting cars in urban centres, partly through parking bans, and providing cyclists and pedestrians with safe routes will help to reduce energy consumption. Copenhagen, for example, has banned all on-street parking in the city centre, while providing ample bicycle parking downtown and at rail stations. In California, cities such as San Diego and San Jose are moving back to commuter rail transporation, to relieve congestion and pollution.[27]

Other policies are needed to control urban sprawl. The density of human settlements is not an accident, but results from decisions made by local and regional officials. Careful land-use planning can reduce transportation needs, primarily by increasing development density and consolidating jobs, homes, and services near public transport. Cities can use tax incentives and zoning regulations to achieve these goals.[28]

Some governments have model policies that cut energy bills and enhance self-reliance. Saarbrucken, Germany, for example, cut energy consumption nearly 20% between 1980 and 1989 with a comprehensive conservation programme run by the city's public utility company. Portland, Oregon, approved an energy plan in 1979 to encourage energy conservation in buildings to counter growing energy bills. The city adopted a new programme in 1990 that strengthens existing conservation measures and also encourages a shift from automobiles to buses, light rail, bicycles, and walking.[29]

City policies can also promote the use of renewable energy resources. Portland has an ordinance that protects the right of building owners to capture the sun's rays for heating. Saarbrucken and Berlin are planning to install photovoltaic cells on the roofs of city buildings. And Tucson, Arizona, is planning a 300-ha solar village that will minimize energy needs and maximize the use of renewable resources.[30]

Energy R&D

Energy R&D programmes are also in need of reform. In 1989, the 21 member governments of the IEA spent three-quarters of their $7.3-billion energy research budgets on nuclear energy and fossil fuels (see Table 5). A major change in priorities could free up billions of dollars for the development of renewable sources of energy.

West Germany spent $179 million on nuclear in 1989, more than 36% of its total energy research budget, while Spain spend 51% and the UK 54%. Only one of these countries has even a single commercial nuclear plant under construction. While the problems of radioactive waste disposal and plant decommissioning still need research, costly efforts to

Table 5. Energy R&D spending by IEA governments, 1989.

Technology	**Amount (million $)**	**Share (%)**
Nuclear fission	3 466	47
Fossil fuels	1 098	15
Nuclear fusion	883	12
Renewables	489	7
Conservation	367	15
Other	1 039	14
Total	7 343[a]	100

Note: [a]Column does not add to total due to rounding.
Source: International Energy Agency, *Energy Policies and Programmes of IEA Countries, 1989 Review*, OECD, Paris, 1990.

develop new plant designs – particularly breeder reactors that produce bomb-grade materials – are badly out of date.[31]

Another example of skewed priorities is the $883 million spent on nuclear fusion research in 1989 by the IEA countries – more than was spent on all efficiency and renewable technologies. Any contribution from fusion in the next 50 years is doubtful; a 1990 study by a US Department of Energy advisory committee estimated that the first commercial fusion plant would not be operating until at least 2040.[32]

Other energy boondoggles abound. For example, the UK government, the European Community, and private industry are financing the development of a manufacturing process to convert coal to petroleum. The $65 million to be spent on this extremely carbon-intensive fuel is nearly three times total UK spending on renewable energy research in 1989. In the USA, industry and government plan to spend $5 billion in the 1990s to develop so-called 'clean coal' technologies. The new combustion methods lower emissions of sulphur dioxide significantly, but have minimal effect on CO_2. At a time when coal use needs to be cut drastically, investing billions of dollars on ways to use more of it is a clear example of misplaced priorities.[33]

Most developing countries are doing no better. India, for example, has a huge and costly nuclear research establishment that for three decades has contributed almost nothing to the country's energy supply. Less than 1% of the Indian government's energy outlays go to renewable sources (excluding large hydroelectric dams), even though renewables, especially fuelwood, account for 40% of the country's energy use.[34]

The challenge in India and around the world is to re-prioritize research spending so that it reflects today's needs, rather than the political clout of existing industries. In the USA, for example, the National Research Council issued a 1990 report recommending that 10% of the civilian energy research budget be reallocated from magnetic fusion and fossil fuel research to conservation and renewable programmes. That would provide efficiency and renewables with around $300 million more each year, a 77% increase.[35]

In all IEA countries, only $856 million was invested in renewables and improved efficiency research in 1989, down from $931 million the previous year. Indeed, measured in real dollars, spending on these programmes declined throughout the 1980s, paced by drastic cutbacks in the USA (see Figure 1).

While research on renewables and efficiency has continued to yield many worthwhile technologies, the pace of progress has been slowed by budget cuts. However, the budgetary nadir of these programmes may be past. Several countries are now planning to increase funding of efficiency and renewables research in response to environmental concerns. In the USA, for example, the fiscal 1991 budget approved by Congress included a 45% increase in renewables spending and a 21% increase for efficiency.[36]

As renewable energy R&D programmes are increased, it is important that they be carefully designed and well-targeted. They should be linked closely to the efforts of private industry, particularly the small businesses that have provided many of the breakthroughs so far. Costly government-funded demonstration projects should in most cases be avoided.

Photovoltaics is a key research priority since it is a technology with great potential for cost reduction and efficiency improvements, yet it is only a minor item in most government R&D programmes. With a substantial increase in spending, widespread use of photovoltaics could be moved up by at least a decade. Low-cost thin-film technologies deserve

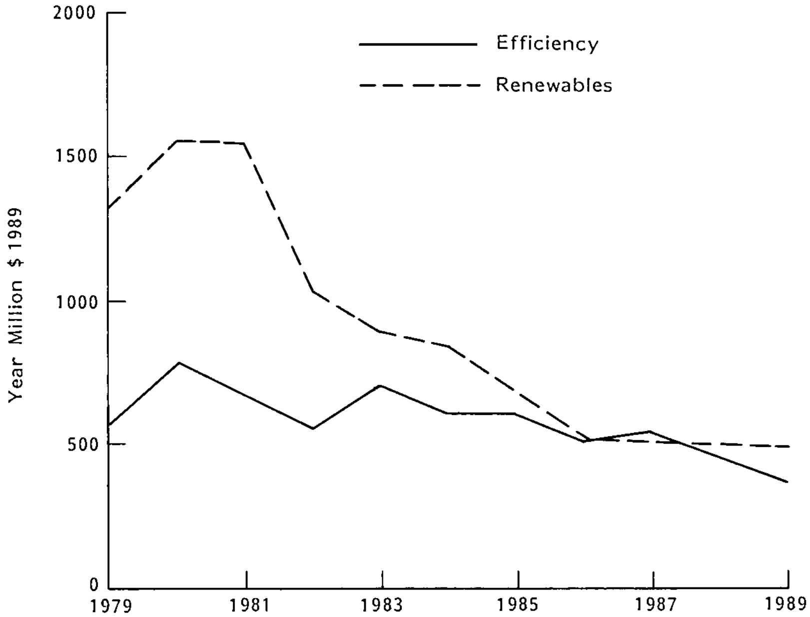

Figure 1. IEA Countries efficiency and renewables budgets for research.
Source: IEA, *Energy Policies and Programmes of IEA Countries, 1989 Review*, OECD, Paris, 1990.

particular support. Also critical is continuing progress in a range of biomass, geothermal, and wind technologies.

Governments would also do well to invest in R&D on the infrastructure needed for a renewable energy system: cost-effective batteries; electric and hydrogen powered automobile engines; fuel cells; and, improved means of storing and moving hydrogen – the most likely energy carrier in a renewables based economy. Because hydrogen is a more corrosive and lighter weight gas than the methane that is used today, there are special technical challenges that must be met if it is to become a standard fuel.

International institutions

With energy problems now a global issue, international energy institutions have important new roles to play. Unfortunately, many of these institutions still reflect the needs and priorities of earlier decades. For example, nuclear power is the only energy source with a United Nations body dedicated to its advancement, the International Atomic Energy Agency (IAEA), which has a 1991 budget of $179 million, with additional voluntary contributions of $70 million expected.

While the IAEA has one essential role – monitoring nuclear proliferation – it also actively promotes the export of nuclear power to developing nations. A similar organization, the Nuclear Energy Agency, exists to facilitate atomic cooperation between industrial countries.[37]

It is time to reconsider the IAEA's promotional role, which does not reflect the position of many of the governments that fund it. The agency's programmes are aimed principally at developing countries, which get 40% of their energy from renewables and less than 1% from nuclear energy. In recent years, many of these poor nations have slowed nuclear expansion, while stepping up their commitment to renewable energy sources. International institutions need to catch up with this shift in priorities.[38]

Broader reforms are also needed, such as more concerted efforts to assist developing countries improve efficiency and harness renewable energy resources. One way of doing this is to increase funding of energy projects by the United Nations Development Program, an organization with a $900-million annual budget. Former West German Chancellor Willy Brandt has suggested the further step of creating an International Solar Energy Agency (ISEA). This body would provide developing countries with support for research, advice on how to build production facilities, and exchanges of information and personnel on renewable technologies.[39]

The problem facing developing countries is in part a shortage of capital and in part a misallocation of funds. Multilateral lending organizations, including the World Bank and the regional development banks, provide developing countries with huge sums for energy projects – more than for any sector except agriculture. Energy accounted for 16% ($3.3 billion) of the World Bank's $21 billion loan portfolio in 1990. These loans attract even more money by encouraging parallel lending by commercial banks and other development institutions. In China in particular, the failure to invest adequately in improved energy efficiency will cause CO_2 emissions from coal plants to soar in the years ahead.[40]

Despite the World Bank's supposed new environmental awareness, only about 3% of its energy and industry loans in 1989 went to improving the efficiency of energy use. Renewables (other than hydropower) received virtually nothing. Significantly increasing multilateral lending for renewables and efficiency is essential if these energy sources are to expand rapidly in developing countries during the 1990s.[41]

Current lending programmes also encourage energy-intensive industries and products, something that is not helpful to most poor countries. By promoting domestic production of efficient refrigerators, air conditioners, electric motors, and other energy-consuming devices instead, poor countries could cut the expected growth in their power sectors by 30% or more, with large economic savings.

In India, for example, instead of building a factory to produce standard incandescent light bulbs, the World Bank could fund the construction of plants to make energy-efficient fluorescent light bulbs. A single $7-million factory could produce 12.3 million bulbs over seven years, enough to save India the equivalent of more than 1 500 MW of coal-burning electrical capacity. That translates into $2.4 billion in savings, mostly from not having to build new power plants.[42]

CONCLUSIONS

The transition to a renewable energy based economy will inevitably reshape many aspects of today's societies. While some of the changes can be anticipated, others can only be guessed at. Overall, however, a sustainable energy system promises to be cleaner and more secure. And while the energy sources may be more expensive, the energy system as a whole will likely be far more economical.

Achieving such a future can only occur with the accelerated reform of energy policies. Most countries still have a long way to go, but there is a new sense of urgency as the public reacts to the threats posed by the greenhouse gases building in the atmosphere.

Some of the biggest obstacles to change are the politicians who are captive to today's energy industries. The halls of the US Congress, for example, are filled with lobbyists for powerful industries – ranging from oil to coal to nuclear power – and their policy agenda still rules. Ironically, while their political power remains, these industries no longer provide many jobs. As more such positions are eliminated in the 1990s, the political power of these industries will weaken.

The world has in a sense already embarked on the next great energy transition – under the pressures of economic, environmental, and social limits that have made the old system unsustainable and obsolete. The main danger is that new energy systems will evolve too slowly, overtaken by environmental problems and the social and economic upheavals that could accompany them.

Societies, therefore, have only a few short decades to achieve a sustainable energy economy. In the end, the key to overcoming the political barriers is to demonstrate that a solar economy would have major advantages over today's dirty and crisis prone fossil fuel-based systems. As the opportunities become clearer, the political momentum for change will build.

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Chapter 17

Renewables and the Full Costs of Energy

Olav Hohmeyer

The central obstacle for a widespread use of renwables are the relative prices of these forms of energy not their availability. The paper shows that the present prices of non-renewable energy sources are heavily subsidized by not including the costs of health and environmental damages as well as costs handed on to future generations. If these costs are taken into account the relative costs of renewables look far more favourable than present market prices show.

Keywords: Renewable energy; External effects; Social costs

In his article introducing the series of papers on renewable energy Jackson[1] poses the question 'Is renewable energy our greatest hope to bring a satisfactory resolution of the 'thermodynamic interlude' or will it prove to be a deceitful signpost, a false promise on the inevitable road to disorder?'. This question can be split up into two parts. First, we have to ask whether renewables will be able to supply close to 100% of human needs for energy services in the long run? If this is possible, the second question will be, at what cost can these energy services be delivered?

Previous papers in the series have shown that solar energy is received by the earth in abundant quantities as compared to our present use of energy. Sørensen[2] gives as estimated recoverable energy stream received by the earth of about 1 000 TW with a total annual energy income (resource base) of about 90 000 TW. According to the World Development Report 1990[3] worldwide consumption of technical energy amounted to about 70 000 h/year in 1988. If we consider an average availability of renewable resources of 1 000 TWh/year – a rather modest assumption – about 70 TW of capacity would be required to cover the world's present demand. Thus, we can conclude that the availability of renewable energy resources will not pose a problem.

This brings us to the second part of the question, the cost of the energy drawn from renewable sources. Presently a standard argument is that renewables will play a minor role in the future energy supply because this form of energy is too expensive. In the long run this argument cannot hold because non-renewable energy sources will be exhausted. At that point in time mankind will have to fall back onto renewable energy sources at any price, because in many instances energy cannot be substituted as a production input or as an essential input into consumption activities. This point of exhaustion for non-renewable energy sources may be a few hundred years in the future if no restrictions are applied.

However, the present discussion on global warming due to the anthropogenic emissions of greenhouse gases, points out that fossil fuels cannot be used at the present pace for decades and centuries to come, if we do not want to endanger global climatic stability. At the same time nuclear fission will only be able to extend our time frame if we resign ourselves to breeder technology with all the potential risks of plutonium fuel cycle and at energy costs which can be guessed at today. It is presently unknown whether nuclear fusion will ever be able to contribute significantly to the energy supplies of mankind, not to speak of the actual costs of such energy even if it could be supplied commercially. Thus, renewable energy may already be needed to supply a major part of the energy used by mankind a few decades from now. Consequently our question of relative costs boils down to a short-to mid-term comparison of renewable energy sources with presently established conventional energy systems.

COSTS TO BE CONSIDERED

The statement that renewable energy sources are too expensive to be used substantially in the short or mid

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term is generally based on a very narrow definition of costs. Cost comparisons usually just take into account the so called 'internal' cost elements involved in the production and distribution of a product. Other cost elements which are payed for by third parties not involved in the production or consumption of the product do not show up in prices and are not considered in standard cost comparisons. These cost elements are normally referred to as external or social costs.[4] In this paper the term social costs will be used. Examples of such social cost elements for energy production and use are: the damage done to forests by acid rain, which are paid for by the forest owners; the consequences of massive global warming due to anthropogenic emissions of greenhouse gases; or the health impacts of major nuclear reactor accidents such as Chernobyl. No energy consumer is charged any of these costs, which result from the use of conventional energy sources.

If conventional energy sources and different technologies for the utilization of renewable energy sources are compared with respect to the levels of social costs incurred, it appears that most renewables have considerably lower social costs. Thus, the seemingly cheap conventional energy sources may be rather expensive to society. If this is the case, the statements regularly made on the comparative internal costs may be vastly misleading and investment decisions taken on these grounds may acrue substantial losses to society.

The question of relative social costs of electric power had been heavily discussed internationally since 1988 when a first comprehensive report on the subject[5] was published. This paper will try to summarize the results of that discussion and to draw some first conclusions with regard to the question of the relative total costs of an energy supply strategy based on renewable energy sources.

SOCIAL COSTS TO BE CONSIDERED

There are a number of different energy costs categories born by third parties which ought to be taken into account in the comparison of different energy technologies. The following list gives an impression of the range of effects to be considered:

- Impacts on human health: short-term impacts like injuries; long-term impacts like cancer; intergenerational impacts due to genetic damage.
- Environmental damages to: flora; fauna; global climate; materials.
- Long-term costs of resource depletion.
- Structural macroeconomic impacts such as employment effects.
- Subsidies such as: R&D subsidies; investment subsidies; operation subsidies; subsidies in kind for: infrastructure and, evacuation services in case of accidents.
- Cost of an increased probability of wars due to: securing energy resources (eg the Gulf War); proliferation of nuclear weapons know how through the spread of 'civil' nuclear technology; costs of the radioactive contamination of production equipment and dwellings after major nuclear accidents; and
- Psycho–social costs of: serious illness and death; relocation of population due to construction or accidents.

This list of possible costs excluded from the normal pricing of energy is not exhaustive but it gives an impression of the range of costs which need to be considered before we may conclude that a certain energy technology is too expensive to be used.

Although it is relatively easy to enumerate a substantial number of social cost categories, which are obviously not taken into account today, it is rather difficult to quantify many of these effects and to put monetary values on them. As in the case of global warming due to anthropogenic emissions of greenhouse gases, we can describe a number of probable effects in qualitative terms while we can only guess others. The latest computer models allow us to come up with some first quantifications of probable global temperature rises, but a sound analysis of the damages incurred and the damage costs to be expected seems presently impossible. We can only guess possible orders of magnitude of such damages. In general we are in the situation of a navigator trying to estimate and compare the size of different icebergs ahead of him while he can only see the tips of these icebergs in the fog.

So far most empirical studies of the problem have focussed on a few problem areas, mostly on effects on human health and environmental damages.[6] It should be pointed out, however, that there is a growing literature addressing different facets of the problem at the theoretical as well as at the empirical level.[7]

EMPIRICAL EVIDENCE ON SOCIAL COSTS

The empirical evidence presented here is based on the present author's latest research on the subject[8] taking into account much of the international discussion of the last three years. This work was centred around a comparison of conventional electricity generation based on fossil and nuclear fuels with wind energy and photovoltaics applied in Germany. These areas of social costs covered are: environmental effects; impacts on human health; depletion costs of non-renewable resources; structural macroeconomic effects; and, subsidies. Due to the scarce availability of empirical data and some fundamental problems in monetizing, a number of effects have *not* been quantified or specified in monetary terms by the author so far.[9]

Accordingly one should interpret the results presents in the following as a preliminary overview producing rather crude figures. Wherever doubt exists, assumptions have been made favouring conventional energy and counter to the underlying hypothesis – that the social costs of systems using renewable energy sources are considerably lower than those of systems using conventional energy. Thus, the author feels confident that the difference in the real social costs between the renewables considered and the conventional electricity generation in Germany is even larger than these results show.

The estimated specific health and environmental costs of electric power production from fossil fuels have been based on available studies trying to monetize the overall damages of air pollutants in Germany. Little information is available on the possible damages of CO_2 emissions through global climatic changes. In general the social costs of environmental and health impacts have been measured as roughly attributable damage costs. In contrast to this approach other authors favour control cost estimates as proxies for the actual damage costs, as these are easier to analyse, while some advocate contingent valuation procedures like 'willingness-to-pay' analyses, which allow a broader range of impacts to be covered than direct costing. Because the control cost approach allows for a substantial level of arbitraryness due to the emission level allowed and because the contingent valuation methods result in somewhat less reliable results, these approaches have been chosen for the analysis only in rate cases. Control costs have been used for some first estimates on CO_2 emission impacts through global climatic change. The figures used are based on an overview of US studies on the subject published by Koomey.[10]

As the author has shown in other publications[11] there is strong evidence that the prices of non-renewable energy sources do not reflect long-term scarcity, because major aspects of intertemporal allocation like sustainability and intertemporal justice are presently disregarded in favour of extremely high and wasteful energy consumption. If energy prices are to steer long-term sustainability, simple models for the calculation of reinvestment costs and appropriate surcharges need to be drawn up. First estimates of such costs are included in the figures quoted in the following.[12]

In the case of macroeconomic effects the structural differences in the production and consumption resulting from different energy scenarios have been analysed. These are mainly changes in GNP and employment.

AGGREGATED RESULTS AND COMPARISON OF SOCIAL COSTS

When the quantified social costs of conventional energy systems for the production of electricity based on fossil fuels are totalled and standardized for the production of 1 kWh, gross social costs in the range of 0.03 to 0.16 DM/kWh result (1989 DM). (The value of 1 DM at the time of writing is about US$.6 or approximately £0.37.) For electricity generated in nuclear reactors (not considering fast breeder reactors) gross social costs in the range of 0.1 to 0.7 DM/kWh result. A weighted average for these gross social costs according to the fuel composition found in (West) Germany's electricity generation in 1984 is 0.05 to 0.29 DM/kWh. Table 1 summarizes the social costs of different means of electricity generation quantified in monetary terms. In order to facilitate a net analysis of the social costs (or benefits) of renewables the social cost figures for conventional electricity carry positive signs in Table 1, while each negative effect of renewables shows a negative sign. In this way the calculation of the difference in the social costs can easily be done by adding position d.1 through d.4 for wind energy (e.1 through e.4 for PV) including the avoided average gross social costs of conventional electricity generation as position d.4, which is the total calculated in part c of the Table.

When one considers the social costs and benefits of electricity generated by wind energy – with the social costs of present electricity generation included as avoided costs (d.4) – total social net benefits in the range of 0.05 to 0.28 DM/kWh result. This can be considered as a probable range for the minimum social net benefits of wind energy. The sum of net social benefits for photovoltaic electricity supplied to the public grid lies between 0.06 and 0.35 DM/kWh after all netting is done. Again, this is only an estimate of a probable range for the minimum social

Table 1. Comparison of the social costs calculated by Hohmeyer in 1988 and the results of recalculations performed in 1990 (all figures in Pf/kWh (1982)).

	Hohmeyer (1988)	New calculations (1990) including CO_2 Emissions 1982	New power plants 1990
Gross social costs of electricity generated from fossil fuels (all figures are estimated minimal social costs)			
Environmental effects	1.14 – 6.09	2.6 – 10.67	2.05 – 7.93
Depletion surcharge (1985)	2.29	0.67 – 4.71	
Goods and services publicly supplied	0.07	0.06	
Monetary subsidies (including accelerated depreciation)	0.32	0.30	
Public R&D transfers	0.04	0.02	
Total	3.86 – 8.81	3.65 – 15.96	3.11 – 13.03
Gross social costs of electricity generated in nuclear reactors, excluding breeder reactors (all figures are estimated minimal social costs)			
Environmental effects (human health)	1.20 – 12.00	3.48 – 21.0	
Depletion surcharge (1985)	5.91 – 6.23	4.88 – 47.72	
Goods and services publicly supplied	0.11	0.11	
Monetary subsidies	0.14	0.14	
Public R&D transfers	2.35	1.46	
Total	9.71 – 20.83	10.06 – 70.13	
Average gross social costs of the electricity generated in Germany in 1984		Fossil power plants 1982	New fossil power plants 1990
Costs due to electricity from fossil fuels (weighting factor 0.705[a])	2.87 – 6.56	2.58 – 11.25	2.19 – 9.19
Costs due to electricity from nuclear energy (weighting factor 0.237[b])	2.48 – 5.32	2.38 – 16.2	
Total (conventional electricity)	5.35 – 11.88	4.96 – 27.87	4.57 – 25.81
Net social benefits of wind energy			
Environmental effects (noise)	(−)0.01	(−)0.01	
Public R&D transfers (estimate)	−0.26 – (−)0.52	−0.16 – (−)0.33	
Economic net effects	+0.53 – (+)0.94	+0.47 – (+)0.78	
Avoided social cost of present electricity generation	+5.35 – (+)11.88	+4.96 – (+)27.87	(+)4.57 – (+) 25.81
Total social benefits rounded to two digits	+5.6 – (+)12.3	5.26 –28.32	4.87 – 26.25
Mean	(+) 8.9	16.8	15.6
Net social benefits of solar energy (PV)			
Environmental effects	(−) 0.44	(−)0.44	
Public R&D transfers (estimate)	−0.52 – (−) 1.04	−0.33 – (−)0.65	
Economic net effects (not including 1982 figures)	+2.40 – (+) 6.65	+2.35 – (+)8.35	
Avoided social cost of present electricity generation	+5.35 – (+)11.88	+4.96 – (+)27.87	(+)4.57 – (+)25.81
Total social benefits rounded to two digits	+6.8 – (+)17.1	+6.54 – (+)35.13	(+)6.16 – (+)33.07
Mean	(+)11.9	20.8	19.6

Notes: [a] Old weighting factor 0.7444; [b] Old weighting factor 0.2556.
Source: Hohmeyer, *op cit*, Ref 4, p 8.

net benefits. All assumptions underlying these figures minimize the advantages of renewable energy sources. Therefore, in cases of doubt, the probable social benefits of the renewable energy sources analysed are considerably greater than these figures show. This point has been borne out by all national and international discussions on the first results published by this author.[13]

Even without including all social costs and even with a deliberate bias against renewable energy sources, the net social benefits in monetary terms of wind and photovoltaic energy are comparable with the basic market prices of conventionally generated electricity. Thus, any statement on the 'high relative costs of renewables' has to be reconsidered in the light of a full cost analysis taking into account the substantial differences in social costs between conventional electricity generation and renewables. The handling of the issue of social costs may have a considerable effect on the time schedule for the market introduction and diffusion of seemingly expensive technologies utilizing renewable energy sources.

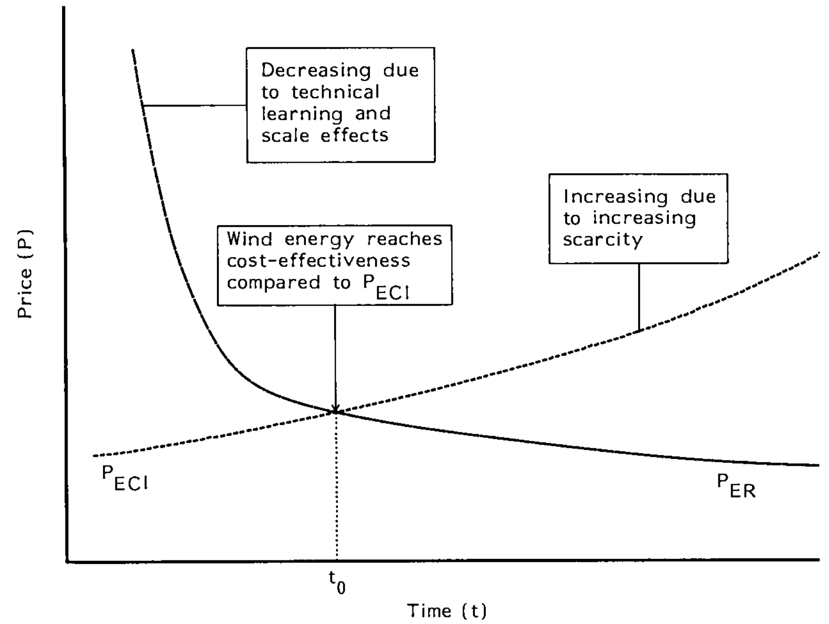

Figure 1. Cost development of two competing technologies for electricity generation over time (no social costs considered).

Source: Hohmeyer, *op cit*, Ref 14.

Notes: P_{ER}: wind energy as an example for renewable energy sources; P_{ECI}: conventional electricity, only internal costs.

EFFECT OF SOCIAL COSTS ON THE COMPETITIVE SITUATION AND MARKET DIFFUSION OF RENEWABLES

How can the impact of considering social costs on the competitive position of a new technology *v* an established one be analysed? One way is to examine a two-product market, as Figure 1 portrays. The costs of the established technology are increasing gradually due to rising exploration and mining costs, for example, while the costs of the new technology based on renewable energy sources are decreasing considerably over time due to technological learning. One can show such developments empirically for conventional electricity and wind or solar energy. At the point t_0, the new energy technology reaches cost effectiveness if one considers no social costs. The substitution process can start at t_0.

Figure 2 shows the effect of including the net social costs. These are defined as the difference between the social costs of conventional electricity generation and those of the new technology. A static application of the social costs for a base year (eg 1988) results in a parallel projection of conventional electricity's market price curve. This results in a new intersection with the renewable energy cost curve and shows that the new energy technology reaches cost effectiveness at $t_0 - \Delta\text{-}t$ at t_1. If the social costs reach a sizable order of magnitude, then a distorted competitive situation results: The wrong price signals are given through the markets to the potential investor for the choice of energy technologies.

Because cost effectiveness does not lead to instant technology substitution but to a substitution – or market diffusion – process that may easily stretch over 20 or more years, one can picture the impact of not considering social costs as a shift of $\Delta\text{-}t$ in the new technologies market penetration curve as shown in Figure 3. If one does not consider social costs, then the whole diffusion process is delayed by this time span as compared with the best possible diffusion time schedule for society.

The social costs empirically quantified in Table 1 are applied in the following analysis of the future competitive position and market diffusion of wind and photovoltaic solar energy. Figure 4 shows the impact of including social costs on the competitive situation and on the resulting market diffusion of wind energy systems in Germany. All assumption for this analysis are given in Table 2. It should be pointed out that there are different assumptions on the percentage of the electricity produced, which is fed back into the grid for wind energy systems (80%) and photovoltaics (50%). This explains the different

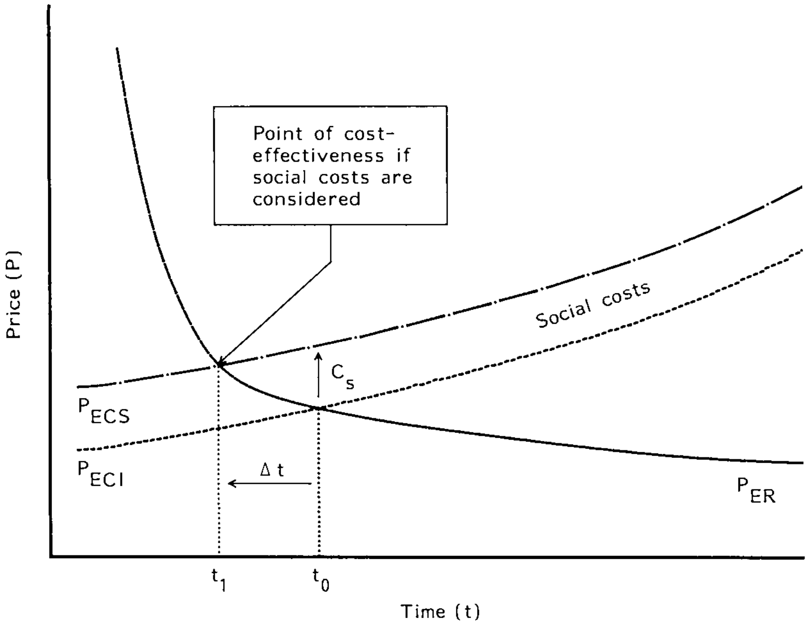

Figure 2. Cost development of two competing technologies for electricity generation over time (social costs considered).

Source: Hohmeyer, *op cit*, Ref 14.

Notes: P_{ER}: wind energy as an example for renewable energy sources; P_{ECI}: conventional electricity, only internal costs. P_{ECS}: conventional electricity including social costs.

prices of conventional electricity which the renewables have to compete against, as the buyback rates are lower than the avoided costs for electricity used for own consumption.

For the electricity costs of small wind energy systems of 50 to 100 kW nominal power, a cost curve has been derived on the few available German wind energy cost figures for the period 1980–86 and on well documented Danish wind energy data for the years 1975–85. As we see from Figure 4(a) the German wind energy cost curve intersects with the market price curve of the electricity to be substituted at point *A*(2002). At this point in time wind energy produced by a private autoproducer is competitive with the electricity from the grid which is to be substituted at market prices not including social costs.

Adding the lower range of the estimated minimum net social costs (0.05 DM/kWh based on new fossil power plants) to this market price curve results in a second curve for the substituted electricity where point *B*(1991) is the new point of cost effectiveness for wind energy. Adding the upper range of the minimum net social costs of electricity (0.26 DM/kWh based on new fossil power plants) to the market price of substituted electricity gives a third intersection *C*(1981) as new point of cost effectiveness for wind energy. Figure 4(b) shows the resulting change in market penetration of wind energy systems resulting from this altered competition situation. We can conclude that, including social costs, wind energy is competitive considerably earlier than market prices show. Accordingly, the market penetration of wind energy systems starts much earlier.

Figure 5 illustrates the situation for photovoltaics in Germany competing with electricity from the grid. The cost degression curve shown has been estimated on the basis of eight different studies on photovoltaic energy cost developments. Later comparison to other analyses has shown the estimated cost degression to be rather conservative. For a more favourable climate such as southern Spain or southern California the PV costs can almost be divided by factor two due to the greater amount of solar radiation per square metre and year. While the cost of electricity generation in isolated locations on the basis of diesel generators may be high as 0.5 to 1.5 DM/kWh depending on the specific transportation costs.

As in the case of wind energy, intersection *A*(2019) gives the point of cost effectiveness for photovoltaics if no social costs are considered. Including the lower estimate of the net social costs as compared to conventional electricity (based on new technology for fossil plants) of 0.06 DM/kWh leads

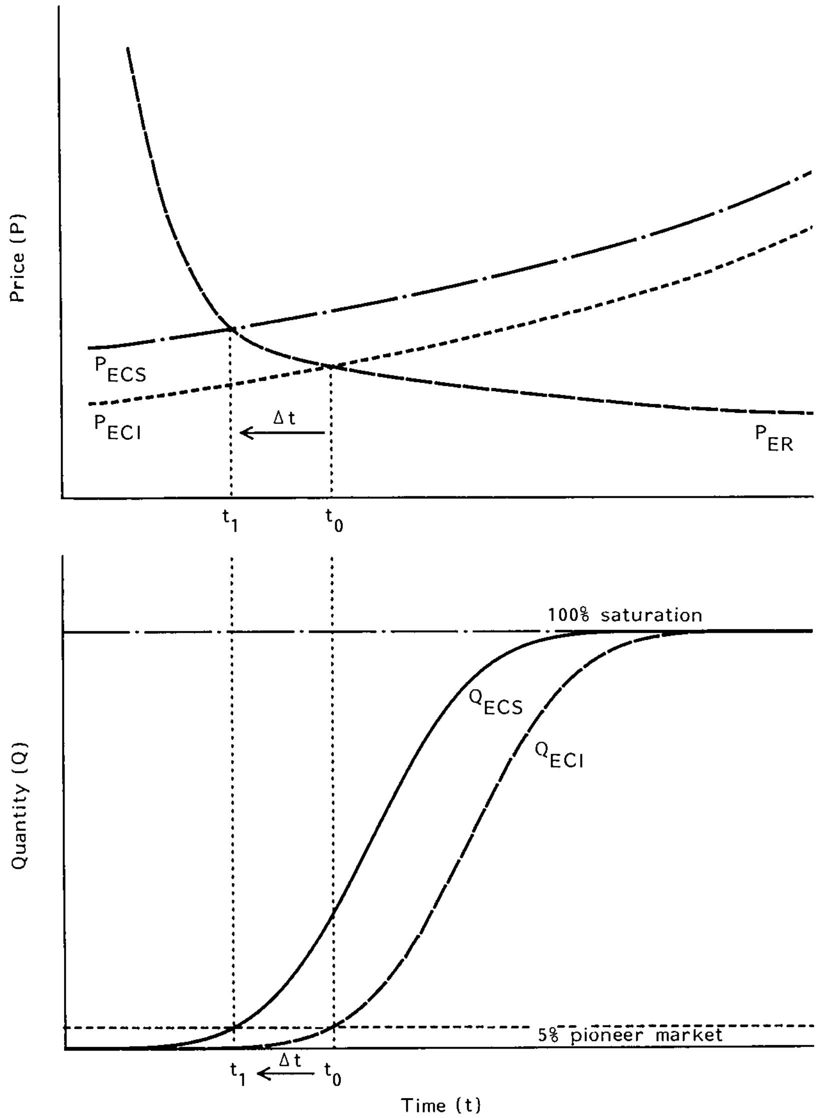

Figure 3. Market diffusion of wind energy due to handling of social costs.

Notes: Q_{ECI}: market diffusion curve of wind energy (only internal costs); Q_{ECS}: market diffusion curve of wind energy taking social costs into account; P_{ER}: wind energy as an example for renewable energy sources; P_{ECI}: conventional electricity, only internal costs. P_{ECS}: conventional electricity including social costs.

to considerably earlier cost effectiveness at $B(2014)$ with the inclusion of the higher estimate of 0.33 DM/kWh (new fossil plants considered) giving an even earlier point $C(2002)$ of reaching competitive cost. Figure 5(b) illustrates the shifts in market penetration accordingly. Due to the substantially higher costs of photovoltaics today, the inclusion of social costs will not have an instant effect on its market introduction as in the case of wind energy. Considering the short- to mid-term future situation one or two decades from now, the inclusion of social costs changes the competitive situation and market diffusion of photovoltaics dramatically.

CONCLUSIONS ON THE REAL COSTS OF ENERGY

After we have seen that renewables can supply more than the necessary energy services needed by mankind we found that – all costs considered – renewables have considerably lower relative costs than market prices show. This is mainly due to the fact that we are subsidizing our present low market prices of conventional energy sources by not accounting for major cost shares due to environmental and health damages as well as by wasting energy

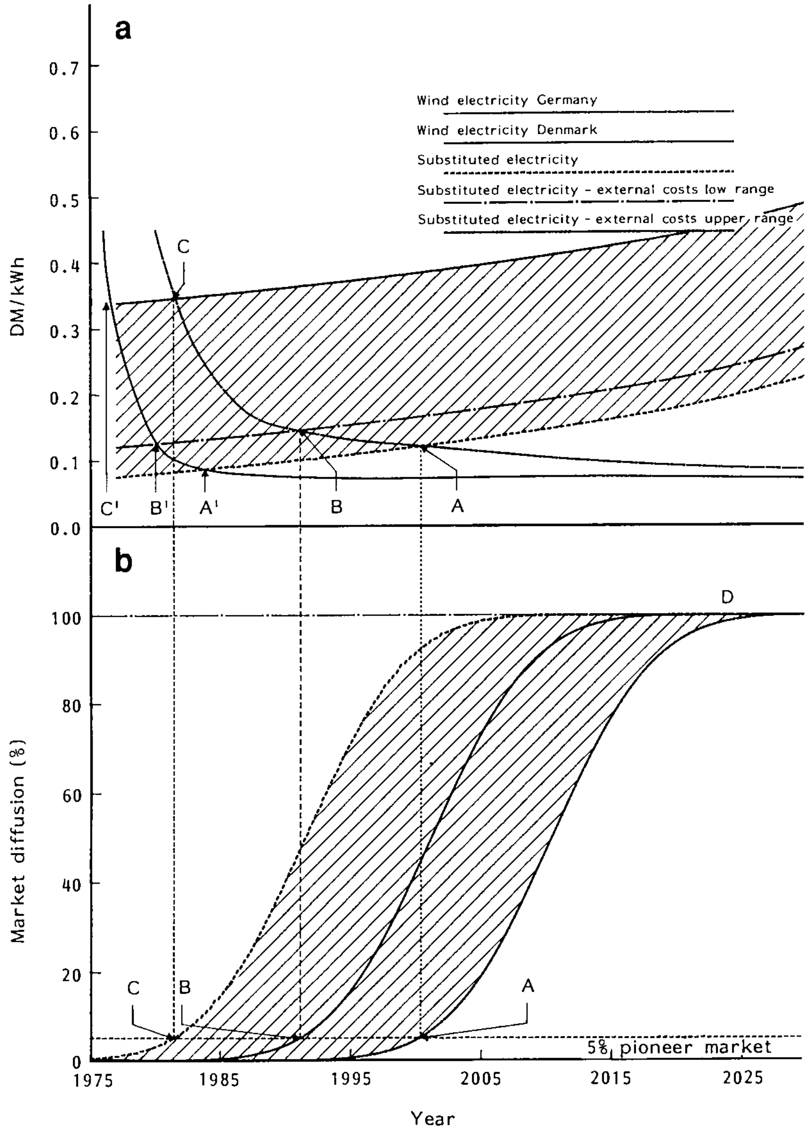

Figure 4. Influence of social costs on starting point of market penetration of decentralized wind energy systems and future market diffusion to year 2030.

Notes: (a) costs for electricity from wind energy compared with costs for substituted conventional electricity; (b) market penetration of wind energy based on costs shown in (a).

at the expense of future generations. Once we stop costs being largely laid on parties not involved in the consumption of the energy we find that renewable energy sources (as well as the rational use of energy) really have cost advantages. This may be concluded, although the results presented are far from being final and exhaustive, because practically all assumptions made in cases of doubt lead to underestimating the true social costs of conventional electricity systems.

An energy policy will be needed to internalize all social cost elements not presently included in energy prices to secure a sound future development of our energy systems and a sustainable development for mankind. This can be done by charging taxes or levies against the activities inducing substantial social costs. If this does not seem to be feasible in the short run, an increase in the buyback rate paid for electricity produced from renewable energy sources can be a starting point for setting things right.

In Germany, the Federal Government has enacted a law which has been in effect since 1 January 1991, to increase buyback rates for electricity from wind turbines and photovoltaic installations to 90% of the electricity rates charged by the utilities to final consumers. This has led to roughly doubling

Table 2. Assumptions underlying the analysis of social costs and the impact on the competitive situation of wind and photovoltaics.

General assumptions	
Price of substitutable conventional electricity (1982)	25.1 Pf/kWh
Working price (62.5 %)	15.6 Pf/kWh
Payment for electricity supplied to the public grid	6.5 Pf/kWh
Real price escalation of conventionally produced electricity	2%/year
Real interest rate for the financing of new investments in wind and photovoltaic machines	5%/year
Market potential for wind and photovoltaic machines	20 TWh/year
'Pioneer market' (5% of the market potential)	1 TWh/year
Time period for the diffusion phase (5% to 95 %)	20 years
Assumptions about wind energy	
Share of wind energy consumed by owner	20%
Share sold to utility	80%
Compound gain of wind electricity (1982)	10.2 Pf/kWh
Compound gain of wind electricity based on working price assumption	8.3 Pf/kWh
Life expectancy of wind energy facilities	15 years
Annuity	9.63 %/year
Operating and maintenance cost	1.5%/year
Wind energy costs in West Germany	
1980	44.8 Pf/kWh
1986	19.6 Pf/kWh
1990	15.0 Pf/kWh
2000	12.1 Pf/kWh
2010	10.2 Pf/kWh
2030	8.4 Pf/kWh
Wind energy costs in Denmark	
1980	12.5 Pf/kWh
1986	9.1 Pf/kWh
1990	7.6 Pf/kWh
2010	7.4 Pf/kWh
2030	7.0 Pf/kWh
Assumptions about photovoltaics	
Share of photovoltaic energy consumed by owner	50%
Share sold to utility	50%
Compound gain of solar current	15.8 Pf/kWh
Compound gain of solar current based on working price assumption	11.1 Pf/kWh
Life expectancy of solar facilities	20–30/years
Annunity	8.02–6.505 %/year
Operating and maintenance cost	12 Pf/W/year
Solar energy costs	
1982	267 Pf/kWh
1990	122 Pf/kWh
2000	62 Pf/kWh
2010	42 Pf/kWh
2020	32 Pf/kWh
2050	26 Pf/kWh

Notes: Pf = Pfennig, 0.01 of a German Deutsche mark (1982 prices); TWh = Terawatt hour; DM = Deutsch Mark (1982 prices).

the buyback rates as compared to 1990. The same law prescribes rates of 75% for electricity from biogas plants and small hydro installations. The resulting rate increases (about Pf8/kWh) corresponds roughly to the average figure of the difference in social costs between conventional and wind or photovoltaic energy.[15]

In the case of wind energy this law has led to a massive expansion in private applications for building permits for wind energy turbines in the coastal areas of Germany, which have average wind speeds above 5m/second.

If other countries will follow this example, the only question left on the widespread introduction of renewable energy sources is how fast these should or need to reach a 50% share in the global supply of energy services, or when do we need to approach 100%?

Certainly renewable energy will be *the* resolution to the 'thermodynamic interlude' and not just a

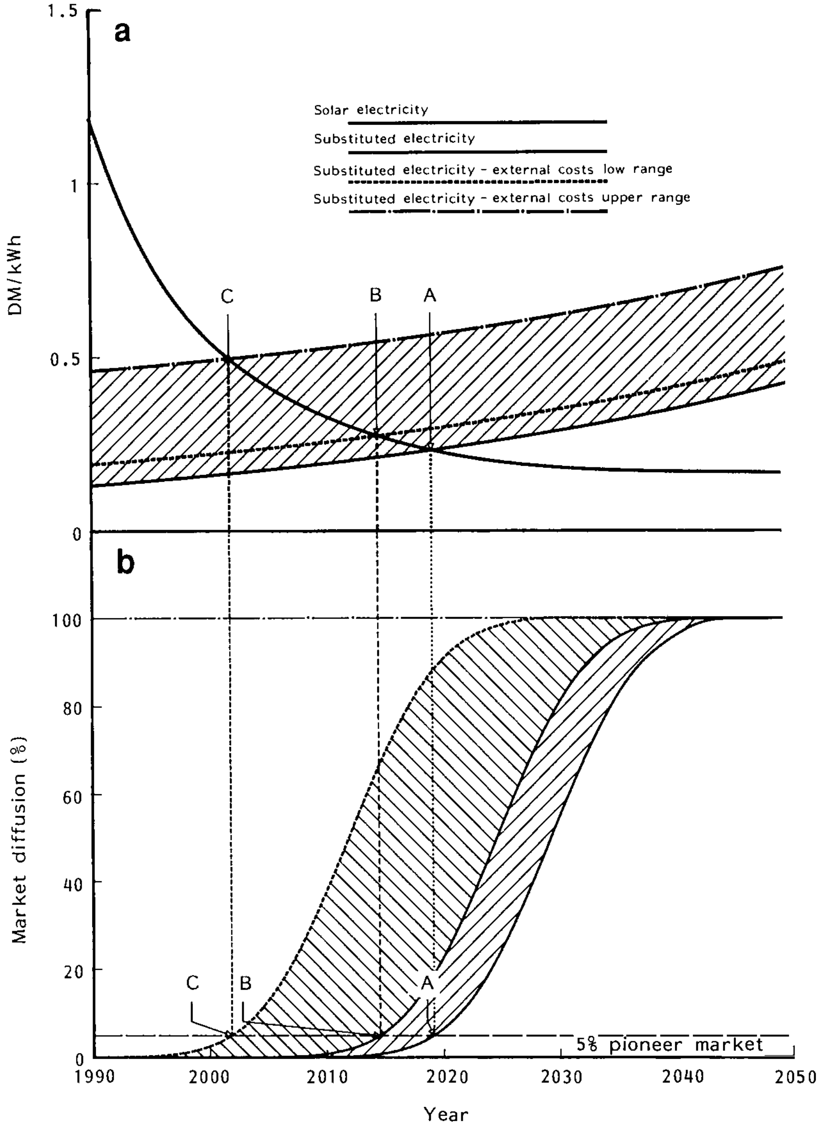

Figure 5. Influence of social costs on starting point of market penetration of decentralized photovoltaic systems and future market diffusion to year 2040.

Notes: (a) costs for photovoltaic electricity compared with costs for substituted conventional electricity; (b) market penetration of photovoltaics based on costs shown in (a).

deceitful signpost, a false promise on the inevitable road to disorder. Keeping the full costs of different energy sources in perspective this turns out to be considerably less costly than first glance evidence suggests.

[1]Tim Jackson, 'Renewable energy – great hope or false promise?', *Energy Policy*, Vol 1, No 1, January/February 1991, pp 2–7.
[2]Bent Sørensen, 'Renewable energy – a technical overview', *Energy Policy*, Vol 19, No 4, May 1991, pp 386–391.
[3]World Bank, ed, *World Development Report 1990*, Oxford University Press, New York, USA, 1990.
[4]According to neo-classical economic theory internal and external costs add up to social costs. Because the neo-classical definition of external costs again excludes certain cost elements of the production process handed on to third parties, Kapp (K. William Kapp, *The Social Costs of Private Enterprise*, Harvard University Press, Cambridge, MA, USA, 1950) criticizes this definition as being to narrow for analytical purposes. He suggests using the term 'social costs' to cover all cost elements of production and consumption processes handed on to third parties. As discussed in detail by the author in his original publication on this subject (Olav Hohmeyer, *Social Costs of Energy Consumption*, Springer-Verlag, Berlin, Heidelber, New York, 1988), the term 'social costs' will be used in this paper according to Kapp's definition.
[5]Hohmeyer, *Ibid*.
[6]Like the extensive US study by R.L. Ottinger *et al*, *Environmental Costs of Electricity*, Oceana Publications, New York, London, Rome 1990; or F. Barbir, T.N. Veziroglu and H.J. Plass, 'Environmental damage due to fossil fuel use', *International Journal for Hydrogen Energy*, Vol 15, No 10, 1990, pp 739–749.

[7]Two collections of papers on the subject should be pointed out besides the publications already mentioned: the special issue on 'Social and Private Costs of Alternative Energy Technologies', *Contemporary Policy Issues*, Vol VIII, No 3, 1990, containing about 30 papers on the subject; and, second, a report on a German-USA workshop on the subject '*External Environmental Costs of Electric Power Production*' O. Hohmeyer and R.L. Ottinger, eds, Springer-Verlag, Berlin, Heidelberg, New York, 1991, containing about 20 papers on the topic.

[8]See Olav Hohmeyer, 'Latest results of the international discussion on the social costs of energy – how does wind compare today?', *Proceedings of the 'European Community Wind Energy Conference'* Madrid, Spain, 10–14 September 1990, H.S. Stephens and Associates, Bedford, 1990, pp 718–724; and Hohmeyer, *op cit*, Ref 4.

[9]These include: the psycho-social costs of serious illness or deaths as well as the costs to the health care system; the environmental effects of the production of intermediate goods for investments in energy systems and the operation of these systems; the environmental effects of all stages of fuel chains or fuel cycles (specifically in the case of nuclear energy); the full costs of man made climatic changes; the environmental and health costs of routine operation of nuclear power plants; hidden subsidies for energy systems; costs of an increased probability of wars due to: securing energy resources (eg the Gulf War); proliferation of nuclear weapons know how through the spread of 'civil' nuclear technology; and costs of the radioactive contamination of production equipment and dwellings after major nuclear accidents.

[10]Jonathan Koomey, 'Comparative analysis of monetary estimates of external costs associated with combustion of fossil fuels', New England Conference of Public Utilities Commissioners, ed, *Environmental Externalities Workshop – Papers Presented*, Portsmouth NH, USA, 1990.

[11]See eg Olav Hohmeyer, 'Least-cost planning und soziale kosten', Peter Hennicke, ed, *Least Cost Planning – Ein neues Konzept zur Regulierung, Planung and Optimierung der Energienutzung*, Springer-Verlag Berlin, Heidelberg, New York, 1991.

[12]For an extensive discussion of such approaches see: Olav Hohmeyer, 'Adaequate berücksichtigung der erschöpfbarkeit nicht erneuerbarer ressourcen', paper presented at the Seminar, *Identifizierung und Internalisierung externer Effekte der Energieversorgung*, Freiburg, Germany, 19 April 1991.

[13]Hohmeyer, *op cit*, Ref 5.

[14]Source: Olav Hohmeyer, 'Social costs of electricity generation: wind and photovoltaic versus fossil and nuclear', *Contemporary Policy Issues*, Vol VIII, No 3, July 1990, pp 255–282.

[15]Hohmeyer, *op cit*, Ref 4, Table 1.

Chapter 18

Renewables and the Privatization of the UK ESI

– a case study

David Elliott

The privatization of the UK electricity supply industry (ESI) was expected to be likely to improve the commercial prospects of at least some renewable energy technologies, especially given the introduction, in parallel, of a protected market/cross subsidy for renewables via the non-fossil fuel obligation. Although some projects have benefited from the new arrangements, this paper suggests that on balance the institutional and strategic uncertainties and the tight contract conditions imposed had a negative impact, at least initially. Alternative, more interventionist, support policies are discussed, drawing on examples from the USA and Denmark.

Keywords: Renewables; Privatization; Subsidies

The UK has amongst the worlds best renewable energy resources – particularly wind, wave and tidal, with for example the ultimate technically feasible contribution put by the CEGB at around 18% of electricity demand by 2030.[1] The Department of Energy (DOE) view[2] is that renewables could be generating up to 70 TWh of electricity by 2025 at competitive prices – compared to current electricity consumption levels of 250 TWh/year. In addition we might expect some 20 million tonnes of coal equivalent of heat from renewables by 2025. Clearly these are theoretical potentials – and what can actually be achieved will depend crucially on a range of technical, institutional, environmental and economic factors, not least level of funding available. There is some dissention over the level of funding for renewables, with, for example, the 1990 House of Commons Select Committee on Energy report lamenting the 'tiny or declining' R&D budgets for renewables.[3]

With the greenhouse global warming issue still very much to the fore, and the events in the Gulf recasting attitudes to energy once again, perhaps a new approach is called for, with renewables no longer seen as marginal, insurance, technologies, but as part of the mainstream. One of the rationales for the UK electricity privatization experiment was that it could stimulate the development of new technologies like renewables. In this paper we attempt to explore the implications of privatization and other forms of stimulation for renewables.

THE NEW TECHNOLOGIES

We are faced with a whole set of 'new' technologies – based on the use of wind, wave, water, tidal, solar, geothermal and organic sources – all at different stages of development, although some of them are more or less ready for commercial deployment. There are a number of ways in which they might be developed; the most obvious being direct state funding. However, simple mission oriented 'technology push' approaches – based on throwing money at large R&D programmes – may not be appropriate or sufficient. As seems to be the lesson from the UK's Alvey advanced computing program, there is also a need for a market orientated follow through.

The basic case for a more interventionist type of follow through is fairly familiar. New technologies, like renewable energy technology, usually have to challenge existing technologies in existing markets. Inevitably it is an uphill struggle, given that new entrants usually are also in the process of moving from the R&D phase through to commercial-scale deployment.

Governments in general recognize this problem, and if they feel the new technology is strategically

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important, they provide some form of subsidy, to support the move to commercial viability. Support at this level is usually more expensive than providing support for basic research and development – but it is not as expensive as investment in full scale capital projects. It is more like pump priming investment designed to establish commercial lift off.

International experience

With these geneal points in mind, what funding approaches have been adopted so far in relation to renewables? Windpower provides a useful point of reference. In the USA, relatively generous R&D budgets for renewables in the 1970s (eg under President Carter) were followed in the early 1980s by tax concession schemes which led to the so-called Californian wind rush, with 16 000 or so privately-owned wind turbines (1.5 GW total capacity) being installed within a few years, mainly in windfarms in California. This boom, however, was rather chaotic – the machines were often poorly designed and sited, installed just to exploit the tax concession. When this was finally withdrawn in 1985, the industry contracted, but now is, arguably, leaner, fitter and more mature, having benefited from the 'experimental' period. Significantly some 622 MW has been installed since 1985, even if US manufactured machines have been joined by macines from Denmark, the UK and more recently Japan.

In Holland and Denmark a more careful, targeted, approach was adopted. Reasonably generous capital grants for private developers, of up to 40% in Holland for example, were conditional on performance and environmental criteria – including careful attention to location. Attention was also paid to consolidating the industrial infrastructure. In 1989 the Danish government decided that its wind subsidy programme, which had cost a total of $40 million, had achieved its purpose.[4] Some 2 500 wind turbines had been installed (around 300 MW) including several windfarms and, although not without its problems, the Danish wind industry was well on the way to being viable, with a national target set of supplying 10% of electricity by around the year 2000. A similar target exists in Holland.

The UK experience

In the UK, the whole process has been much slower. So far there are only a few individual wind turbine demonstration schemes plus the promise of some windfarms, a series of feasibility studies on tidal barrages, and some ongoing research on geothermal hot dry rock technology, together with some background support work for solar and biofuels: the wave R&D programme was all but wound up following a review in 1982, although a new review is underway.

Compared with many other countries, R&D support for renewables has been relatively low – rising to a peak of £24 million/year or so as at present (around £5 million for wind) but set to fall to near zero by the year 2000, on the assumption that the private sector will take over.[5] This process was meant to be supported by the cross subsidy available to suitable projects, via a levy on fossil fuel burning, introduced within the 'non-fossil fuel obligation' (NFFO) scheme, as part of the privatization arrangements in the UK governments' November 1988 Electricity Act. Under this scheme, the new private Regional Electricity Companies (RECs) in England and Wales are obliged to make power purchase contracts, at levels set by the Secretary of State for Energy, with suppliers of non-fossil fuel generated electricity, the additional cost (over and above the nominal fossil fuel price) being made up via a levey on fossil fuel generation.

Given that initially the NFFO would mainly be satisfied from nuclear plant, with renewables only gradually edging in, the bulk of the levy would go to support nuclear power: the nuclear part of the NFFO was subsequently set at 8.5 GW. However, in April 1989, a 600 MW Declared Net Capacity (DNC) renewable quota was set aside within the NFFO, to be filled in stages by the year 2000. The initial 1990 renewable bids, however, fell outside this quota, simply being part of the initial overall NFFO.

As will be described in more detail later, all did not go too well with this 1990 renewable tranche: the constraints on the availability of the levy (following an EC ruling in March 1990, it would only be allowed to run for eight years) and the tight commercial conditions in the contracts being sought, severely limited the number of projects going ahead. Out of the original 370 or so 1990 applications (totalling around 2 GW installed capacity if the 500 MW Mersey Barrage proposal is included) only 75 were finally accepted (total capacity 170 MW). Some of the original proposals were no doubt non-starters, technically or economically, with 320 or so projects being more commonly cited as the realistic figure (the DNC figure being 1 237 MW, as illustrated in Table 1). However, many of these subsequently dropped out, with the 1998 levy deadline evidently being the main hurdle: most projects needed longer periods of initial support to be commercially viable.

Of course the NFFO-levy was not designed for renewables, it was meant primarily to support nuc-

Table 1. 1990 NFFO applications: December 1989.

Technology	Declared net capacity (MW)
Waste	669
Landfill gas	91
Sewage gas	20
Wind	210
Hydro	16
Tidal	231
Total	1 237

Source: House of Commons Energy Committee, 'The Department of Energy's Spending Plans, 1990–91, HMSO, London, UK, 1990.

lear power. That was the main reason for the EC's insistance on an eight year limit: the negative effect on renewables was unintended. The link up between renewables and nuclear in the NFFO has, in this respect, proved to be unfortunate, at least for renewables, for which the eight-year levy limit has been a major blow. By contrast, nuclear power, now back in the public sector, after the proposal to include it in the sell-off was withdrawn in November 1989, has a whole series of other subsidies available to it. For example up to £2.5 billion has been set aside to help the nuclear industry with its fuel reprocessing, nuclear waste storage, and plant decommissioning costs. Renewables have had few of these advantages and continue to be the poor relative, with the fledgling renewable industry struggling to survive.

To take wind energy again as an example, the Glasgow based engineering firm, James Howden, was one of the UK wind pioneers and broke through into the US market, with a 70 machine windfarm in California. Export led expansion is always difficult, but Howdens was unable to establish a domestic market, and decided, after some expensive teething problems with its California machines, to pull out of windpower altogether – blaming the delays and uncertainties surrounding privatization as at least a contributory reason. The British Aerospace/Taylor Woodrow Wind Energy Group consortium, was also initially successful in the USA, but has so far found it hard to get UK orders, while the blade supplier, Composite Technology, has gone into liquidation, as has the pioneering Northumbrian Energy Workshop wind cooperative, who also blamed privatization for their demise: it had they said initially seemed to be 'an opportunity to sweep clean and get rid of the old ideas' but had fallen foul of 'a political attempt to make it more attractive to shareholders'.[6]

RENEWABLE ECONOMICS AND THE 1990 EC RULING

It is worth reviewing the events surrounding the 1990 NFFO in more detail, since they highlight many of the economic and institutional problems facing renewables.

The economics of renewables, like those of most energy technologies, are very sensitive to the rates of return expected and the period over which the supply contract runs. Given that there are no fuel costs (biofuel and waste fed systems apart) just capital costs plus limited operational and maintenance costs, the longer the contract the better the economic return. Under public sector conditions, long contracts (often for the full lifetime of the plant) with low rates of return (traditionally 5%, but more recently 8%) were the norm, but in the new private sector environment, at least a 11% real rate of term would be expected, along with shorter term contracts. Taking a typical windfarm project as an example, Peter Musgrove from the Wind Energy Group (WEG) calculated that at a 5% real rate of return over a 35 year lifetime, electricity could be supplied at p 3.5/kWh. However at 11% over eight years, the unit cost would rise to p 8.3/kWh.[7] The Department of Energy had set a cap of p 6/kWh for the renewable projects under assessment as candidates for the 1990 fossil fuel levy.

Many of the initial applications assumed 15–20 year contracts, with unit costs therefore falling below p 6/kWh, (eg p 5.7/kWh on WEG's figures for a wind farm over 20 years at 11% rate of return), with the share that they assumed they would get from fossil fuel levy obviously helping to ensure success. On this basis the prospects looked quite good – and the p 6/kWh cap seemed reasonably generous. But as we have seen, this assessment proved to be premature. Some regional electricity companies evidently wanted shorter more flexible contracts, and, more importantly, the EC indicated that it considered that the UK governments plan for the fossil fuel levy, as outlined in the privatization arrangements (with non-fossil powered generation subsidized from a levy – the so called 'nuclear tax' – on private fossil fuelled plants) might be in conflict with the EC's 'fair competition' rules. The main thrust of the EC's criticism was directed against what they saw as a proposed subsidy for nuclear power. The fact that renewables were also meant to benefit from the fossil fuel levy, and would suffer if the levy was blocked by the EC, was incidental and, it seems, was not appreciated by the EC. But in the event an outright ban on the levy was avoided: at the end of March, just before vesting day for the UK's private electricity companies, and following strenuous lobbying by UK representatives, the EC accepted a UK Department of Energy compromise proposal – that the levy should only be allowed to run up to 1998, ie for eight years. This constraint would not seriously limit nuclear power, given that it was back in the public sector and could expect 'internal' state subsidies. However, the limitation to eight years has disasterous implications for renewables, with the consequent eight year contracts making it unlikely that more than a few of the more novel renewable energy projects, like wind farms, could meet the p 6/kWh cap. The UK renewable energy community was seriously shaken by what many saw as a disasterous turn of events.

There was considerable debate over who was actually to blame – the EC or the UK DOE. *New Scientists'* claim that 'the British Government has strangled at birth a large number of proposed projects for renewable energy' was underscored by the views it quoted from Musgrove, who argued that there had been disagreement over the new contact time limits between the division responsibilities for renewable energy and that overseeing privatization, the latter wanting 'the legislation to be as simple as possible without any consideration of what it does for renewables'.[8]

Certainly it seems that it was the UK side that suggested the eight year limitation, and, although this could be seen as a compromise to head off an outright EC ban on the levy, the UK government could have sought to have renewables exempted from the time limit – a proposal that seems likely to have been accepted given the EC's positive policies on renewables. Indeed, in a recent press release, Friends of the Earth[9] have suggested that the EC would still welcome a request from the UK government for renewables to be exempt from the 1998 deadline; they also claim that in fact it was the UK government who '*chose* to apply the same terms' to renewables (author's emphasis).

But leaving speculations like this aside, it does seem clear that the UK governments' tie up of renewables and nuclear in the non-fossil fuel levy, had proved very unfortunate for renewables, with renewables being inadvertantely tarred with the same brush as nuclear by those in the EC opposed to further nuclear subsidies. Subsequently the DOE tried to soften the blow somewhat, but suggesting that the initital price could be higher, as long as it averaged out to 6 p over the whole contract period. Even so, with no sign of the UK government being willing to reapproach the EC to seek exemption from the eight year limit for renewables, the overall mood within the UK renewable energy community by mid-1990 was one of pessimism. For example Musgrove commented at the 1990 British Wind Energy Association (BWEA) conference 'I cannot see how any wind farm can be funded in eight year contracts'. The BWEA[10] commented, in a press release. 'The NFFO . . . in theory should provide a framework to encourage the harnessing of renewable energy. However, the contracts being offered to prospective developers are so short as to make almost all such capital investment commercially unviable'.

THE 1990 NFFO

Nevertheless protracted contract negotiations continued between the various generation companies and the RECs, overseen by the DOE, and the new Office of Electricity Regulation (OFFER). As a result in September 1990, 75 out of the original 370 or so initial proposals were accepted for inclusion in the NFFO, the bulk of them (128 MW total capacity) being biofuel/waste projects, including 25 landfill gas schemes and 86 MW of waste incineration capacity, together with 25 micro-hydro schemes. Only five wind farms (25 MW capacity in total) survived the contract negotiations, along with 2 MW of (already existing) individual wind turbines (see Table 2). Overall, two-thirds of the capacity was attributed to new projects.

The statutory renewable element of the 1990 NFFO (ie the renewable capacity which the regional electricity companies are obliged to contract for from suppliers) was set at 102.25 MW declared net capacity. (taking into account the intermittancy of wind) to be attained by April 1995, this level of capacity then running until 1998, when the levy would end. The 75 projects themselves, if all successful, were expected to result in the installation of some 170 MW of capacity (or around 150 MW declared net capacity) so there was a small safety margin (see Table 2). But the difference between this figure and the total of around 2 000 MW of capacity initially bid for was widely remarked on, as was the long-term capacity target for renewables, also announced in September in the governments' White Paper on the Environment, of up to 1 000 MW by the year 2000.[11]

Friends of the Earth commented 'The Government has squeezed out viable projects by continually changing the rules. The pathetically low and un-

Table 2. First NFFO/renewables order (1990) set at 102.25 MW (DNC) at April 1995.

Agreed contracts Technology	No of projects	Capacity installed	MW (DNC)
Landfill gas	25	35.5	35.5
Hydro	26	11.6	11.6
Bio-gas	8	6.5	6.5
Waste incin.	7	86.0	86.0
Wind	9	28.4	12.2
Total	75	168.3	152.1

Note: To run from 1 October 1990 until 31 December 1998.

ambitious target sums up the governments attitude to the future of renewables', while the BWEA saw the 1990 wind allocation (less than 30 MW installed capacity in total out of the 488 MW worth of initial bids) as 'embarassingly small' compared with countries such as Denmark, the Netherlands and Spain.[12] The point was also regularly made that the NFFO/levy scheme did not cover Scotland – which has a large wind resource.

For its part, the government tried to shift part of the blame on to the renewable energy community, with for example Colin Moynihan, the new minister responsible for renewables, suggesting that the wind operators were 'too poorly prepared'. This was hotly denied by Jim Halliday, President of the BWEA, commenting that it was the way the contracts had been devised and then constantly revised that had been the problem. 'The technology is ready to be harnessed, but the Government has sometimes suddenly changed the goal posts. It is not surprising that prospective wind operators have been unwilling to sign'.[13]

Recriminations and special pleading apart, it does seem clear that the 1990 renewable NFFO exercise had not gone smoothly, especially in relation to some of the more novel options like windpower. In part this was due to the haste in which the whole process was carried out, as determined by the need to complete negotiations in phase with the overall privatization process. The DOE was evidently somewhat surprised by the number of proposals that came forward, and, given that this was the first such exercise they had been involved with, it is perhaps not surprising that there had been some delays and confusions. In this situation, from the DOE point of view, successfully selecting 75 projects might be seen as something of a triumph: some of the original contendors had in any case been rival projects for the same site and some were not technically or financially viable.

The administrative situation will hopefully be improved for the subsequent rounds of the NFFO. Following a DOE review of the 1990 exercise, the Secretary of State proposed that separate sub-tranches for each renewable be introduced for the 1991 round, with 'bands' allocated for each technology (see Table 3) together with separate band prices, based on a competitive tendering process. In part the aim was to support projects that were not ready for the 1990 round – particularly windfarms, with a 25-50 MW (DNC) sub-tranche being proposed for wind projects.[14]

Table 3. Proposed second NFFO/renewables order (1991).

Technology	MW (DNC)
Wind power	25– 50
Hydro	5– 10
Landfill gas	30– 60
Municipal and general industrial waste incineration	50–100
Others (eg sewage gas, combustion of special waste)	15– 30
Total	150–200

Note: To run from 1 January 1992 until 31 December 1998.
Source: DOE, December 1990.

THE 1991 NFFO AND BEYOND

This innovation, although, as we shall see, not without its own problems, seemed to have the desired effect. Around 500 MW of renewable projects were put forward in the 1991 round, according to a survey carried out by *Electrical Review*,[15] swamping the initial 150–200 MW (DNC) NFFO allocation. Similarly, with, according to an estimate by the Friends of the Earth[16], 267 MW of the new wind applications (115 MW DNC), the 25–50 MW (DNC) wind sub-tranche was also heavily over subscribed. In the final allocation, announced, after some delay, on 5 November 1991, more than two-thirds (82.43 MW DNC) of the initial wind projects

Table 4. 1991 NFFO/renewables order actual allocations.

Band	Order	REC's contracts
Waste		
MW DNC	261.48	271.48
No of schemes		10
Price /kWh		6.55
'Other'		
MW DNC	28.15	30.15
No of schemes		4
Price /kWh		5.9
Hydro		
MW DNC	10.36	10.86
No of schemes		12
Price /kWh		6.00
Landfill gas		
MW DNC	48.0	48.45
No of schemes		28
Price /kWh		5.7
Sewage gas		
MW DNC	26.86	26.86
No of schemes		19
Price /kWh		5.9
Wind		
MW DNC	82.43	84.43
No of schemes		49
Price /kWh		11.0
Total	457.28	472.23
No of schemes		122
Eventual cost to Fossil Fuel Levy	(£m/year)	c£130m/year

Source: Department of Energy, 5 November 1991.

were accepted (49 projects), the overall 1991 renewable NFFO being set at 457 MW (DNC) (see Table 4), with 122 projects out of the initial 282 applications being accepted.

This was clearly a significant increase on the initally proposed allocation with, as a consequence, nearly half of the governments' target 1 000 MW by the year 2000 having already been achieved. In response, when announcing the 1991 NFFO in November 1991, the Minister Colin Moynihan indicated that the DOE's new independent Advisory Group on Renewable Energy, which had been set up earlier in the year, would be re-assessing the 1 000 MW target. In evidence to that Group, presented in September 1991, Friends of the Earth had already called for it to be expanded to 3 500 MW, while Greenpeace have been campaigning for a 10% contribution to electricity supply by 2000 implying around 6 000 MW.

If targets of this order are to be considered then it would seem necessary for significant improvements in the NFFO scheme to be introduced. As it is, although the wind element has increased, the bulk of the NFFO is still made up of industrial and domestic waste combustion projects and there have been some signs of environmental opposition to these schemes. For example, following the announcement of the 1991 NFFO, Greenpeace commented 'it is wrong to call incineration a renewable energy. There are continuing, serious doubts about the dioxins and atmospheric pollution that incineration creates'.[17] Although there are obviously ways in which such emissions can be limited, some environmentalists would clearly prefer to emphasize the use of *natural* energy flows ie wind, wave, tidal and solar.

But even leaving that issue aside, a significant expansion of renewables would presumably imply an increasing contribution from some of the more ambitious 'natural flow' options. In the longer term, that would imply consideration of the larger scale options like wavepower and large tidal barrages, as well as off-shore wind, all of which, in turn, would imply the involvement of large companies. In the medium term there could be a role for a wide variety of new projects at the medium scale, if suitable support structures were available. For example, there has already been a call by the Mersey Barrage Company for the introduction of a separate NFFO sub-tranche for the Mersey Barrage[18] and the Open University Energy and Environment Research Group, in its evidence (October 1991) to the House of Commons Energy Committee hearings on renewables, suggested that a separate sub-tranche be established, within the NFFO, for photovoltaic solar cells.

In the shorter term smaller companies might play an increasing part, with small companies often being able to be more innovative. However, while small companies have already played a significant role in the 1990 and 1991 NFFO's, there have evidently been problems. In September 1991 Michael Spicer MP, who, when he was energy minister, had been closely involved with the privatization exercise and the governments' renewable programme, told the Association of Independent Electricity Producers (AIEP), of which he had just been elected chairman, 'it is still a brave small company which attempts to enter the NFFO unless it has the services of a good advisor'.[19] There have been repeated calls from independent producer groups for some form of special support scheme for smaller projects, via, for example, an exemption from the full rigours of the lengthy and costly assessment process, so as to help smaller companies compete with the better resourced larger companies.

Despite these problems, to their credit, some small companies, like Fibropower, were successful in traditional entrepreneurial terms (two of their chicken manure fuelled plants being accepted in the

1990 NFFO). But the going was evidently tough: for example, Peter Edwards, a Cornish farmer and landowner whose windfarm, accepted under the 1990 NFFO, looks like being the first to be completed, had to sell off his dairy herd to raise capital, and that was despite the benefit of a 40% EC grant. According to Edwards, the cost of legal fees and contract registration had been around £35 000. Unsurprisingly, then, some other small developers have been unable to stay the course – second mortgages and the like notwithstanding. For example, despite having undiminished enthusiasms for renewable energy projects, the Welsh based Energy Parks UK windfarm company, which had unsuccessfully put up five windfarm proposals in the 1990 NFFO round, backed off the 1991 round. Others again, like ECOGEN, a small windfarm development company with local bases in Cornwall, Devon and Wales, changed tack. Following an unsuccessful bid in the 1990 round, Ecogen obtained significant financial backing from a USA–Japanese consortium, involving the US Sea West windfarm developers and Tomen, a major Japanese energy and chemicals company.[20] Ecogen put forward 13 windfarm proposals (80 MW capacity) with imported machines likely to be used – possibly the increasing successful Mitsubishi turbine.

In parallel with this internationalization process, economic and industrial concentration seems to be increasing. Perhaps the most significant development has been the (September 1991) creation of a major new windfarm operating company National Wind Power (NWP), 50% owned by National Power (NP), 25% each by the existing Wind Energy Group (WEG) partners, British Aerospace and Taylor Woodrow, WEG itself continuing separately as a wind turbine *manufacturing* company.

While this reorganization could give windpower a boost in the UK, given the involvement of NP, it could also threaten the already weak position of some of the smaller wind farm operating companies. After all NWP has the benefit of some 13 MW of NP and WEG wind farm capacity already agreed under the 1990 NFFO. Equally, the split up of operation and manufacturing may further weaken the UK wind turbine *manufacturing* base. Danish manufacturers, notably Vesta's, have already successfully penetrated the UK market, and Mitsibushi could well follow. If that trend continues, it could be that the UK industry will increasingly focus on windfarm *operation*, buying in turbines from overseas and leaving the commercially more risky manufacturing side to others.

Nevertheless, following the generally favourable result of the 1991 NFFO, and some encouraging signs that the government was 'opening up' on renewables (for example via the establishment by the DOE of the independent Advisory Group on Renewable Energy mentioned earlier), the mood of the renewable energy community overall has lightened somewhat, at least in England and Wales. The fact that the NFFO does not apply to Scotland (or Northern Ireland) has, however, continued to be a major point of contention there, although changes are expected. In addition, following continuing campaigning by pressure groups (like Friends of the Earth), developers (like the AIEP) and professional associations (like the BWEA), there have been suggestions that the 1998 NFFO/levy cut off date may also be removed, at least for subsequent rounds of the NFFO. In November 1991, the Minister Colin Moynihan, announcing the 1991 NFFO, indicated that the government would be discussing this issue with the EC, with a view to being able to extend the contract period for the 1992 NFFO beyond 1998.

For the moment, however, the 1998 cut off remains one of the key problems with the NFFO. As the BWEA[21] put it 'As time passes the 1998 NFFO cut-off will become more and more crippling for wind energy and other renewables as the period for repayment of capital becomes even shorter'.

With the deadline now a year nearer, the need for a rethink is even more urgent. Otherwise if significant tranches of renewables are continued to be accepted, the band prices will have to be artificially increased even further. For example, the band price for wind in the 1991 NFFO was set at p11/kWh, and this price would no doubt have to be increased in each subsequent NFFO.

ALTERNATIVE APPROACHES

While clearly the availability of the NFFO levy must have stimulated some projects that would not otherwise have gone ahead, so far the general lesson seems to be that the privatization arrangements, both institutional and financial, initially hindered as much as helped renewables, particularly the more novel ones like windpower. Certainly that was the conclusion reached by the Watt Committee in its report on renewable energy sources 'New institutional and financial factors would seem to positively harm the prospects of increasing the proportion of electricity supplied by renewable sources'.[22] The changes made for 1991 seems to have improved the situation somewhat, but even so there would at the very least seem to be a case for further improvements (the removal of the 1998 deadline etc) But beyond that, the question arises, what other or additional measures could be adopted?

Most people would accept that public funding must play a role in the R, D&D phase, but that at some point most renewable projects should be able to be independent of state support. The main contested issue is the appropriate level and duration of funding for renewables for the shift from research through to unsubsidized commercial scale deployment. The follow up support provided in the UK so far might be seen to be not only too penny pinching but also too short term – renewables arguably having been expected to be able to stand on their own feet rather too soon. That is not to say they need indefinate periods of subsidy, as the experience in Denmark suggests, but rather that in the UK they need just a few more years of support, less for some options (like wind) more for others (like wave and geothermal). Of course there are exceptions: some options like large tidal barrages, which are one-off projects, are so front end capital intensive that they may need fall scale state support if they are to go ahead, a point made by the Watt Committee, which recommended the use of public sector rates of return for such projects.[23] But most of the rest are smaller scale, more modular and flexible, with incremental improvements possible, as operating experience is gained and technology advances: what seems to be needed is relatively small amounts of pump priming money – tens of millions rather than billions, and in some cases much less. Funding at this sort of level could compensate for the shortfall due to the eight year limitation on the levy, assuming that cannot be removed, and could tease out capital from the private sector. Certainly this is the sort of approach that would be likely to appeal to an incoming Labour government – which presumably would not have cash to fund major new projects itself, but was keen to see renewables developed.

Some of the extra funding could come via the NFFO levy. There are obviously ways in which the NFFO arrangements could be improved so as to stimulate the development and deployment of renewables more effectively. In addition to the continuing pressure from the renewable energy community for the removal of the 1998 levy deadline, and for expanding the NFFO to cover Scotland (and Northern Ireland), there have been calls for more generous 'band prices' to be set. For example in a paper on wind energy, Friends of the Earth proposed an index linked p8/kWh price ceiling, with contracts running over a 15-year period from the start of the project, together with expanded targets for renewables, including a goal of 1 000 MW (DNC) for wind by the year 2005.[24] Friends of the Earth justify the extra cross-subsidy on the one hand on the basis of environmental benefits (eg reduction of CO_2 emissions) and on the other, by the need to take the pressure off environmentally sensitive high wind speed sites (which they claim wind farm developers were having to resort to because of the tight contract conditions). Even so, proposals like this might still be seen as a little over-generous, given that, in the end it would be the consumer who would pay.

There may be ways to ensure the lift off of wind power and renewables without such long periods of relatively high, guaranteed operating subsidies. For example, although there would have to be protections against abuse, capital installation grants and low interest loans might be more appropriate if we are trying to support the less developed technologies.[25] Grant or loan schemes might also be more appropriate for some of the smaller projects. Overall, there would seem to be a need to select and balance appropriate types of financial support for the various phases in the move from 'research' to full scale commercial success.

While much of the basic research has now been completed, there is clearly still a need for more in some areas (eg in photovoltaics, geothermal and wavepower) as well as for more development work, eg to increase energy conversion efficiencies and technical reliability and reduce unit costs. For example the layout of windfarms can be improved to reduce array interaction losses and blade design might be improved by the use of new materials.

A recent report for the US DOE on the potential of renewable energy[26] estimated that while wind turbines on good sites can currently generate at around ¢ 7/kWh, this could drop to around ¢ 4/kWh within around five years if suitable R&D funding was provided making windpower clearly competitive with gas. Given developments like this, the USA might expect the renewables to supply around 28% of toal energy requirements by 2030. To achieve this end, the US report calls for a major expansion of Federal renewable R&D support up to two or three times current levels, involving the allocation of around $3 billion over the next two decades, coupling this initial 'technology push' approach with a 'market pull' incentives approach, based on short-term grants and subsidies for subsequent deployment. In particular it calls for low interest loans, or loan guarantees, to reduce the high risks investors perceive to be involved with new technologies, along possibly with tax credits during the early high risk years. Carefully targeted and phased support and incentives mechanisms of this sort could both stimulate development and deployment, and help renewables to stand on their own feet more rapidly.

UK OPTIONS

Suggestions like this have been seen as almost heretical in the UK in recent years; for example DOE commented: 'Some countries have in the past tackled the institutional issues head on by offering financial incentives in the form of grants or tax concessions in order to stimulate deployment . . . This approach is not favoured'.[27] This point was reinforced by Michael Spicer, then an energy minister, who argued that, while the government was happy to support initial research on renewables, 'the renewable technologies would not be best served in the long term by distorting the market by grant aid or other subsidies for their use'.[28]

Subsequently, this line was softened, eg with the inclusion of renewables in the NFFO and, in general, the simple 'competitive market' approach initially preferred by the government seems to have gradually been modified. Thus, instead of open competition, we now have an overall protected 'non-fossil fuel' quota (for nuclear and renewables), a 600 MW DNC renewable sub-quota, to be filled in stages by the year 2000, and, more recently (December 1990) the introduction, as noted earlier, by the Secretary of State, of a series of designated bands for each renewable within the 1991 NFFO (see Table 3).[29] Although there could still be competition at the margin of the bands, and within them, the overall aim of the new scheme would seem to be to provide protected slots within which selected technologies can prosper subject only to a new price tendering scheme. Under this new procedure, the 1990 unit price ceiling was dropped. Instead, initial bids were made 'blind' by intending suppliers, a fixed 'band price' then being set at a level which would deliver an appropriate tranche of NFFO capacity, the band price then being made available to all acceptable projects that bid at or below it.[30] Quite apart from the issue of the ever nearer 1998 levy deadline which, as we have seen, is likely to force prices for some of the technologies up artifically high, the scheme attracted some criticism from the renewable energy community: for example, it was argued that projects which bid low could, in fact, get a windfall subsidy they do not need,[31] while, alternatively, some developers might collude, albeit illegally, and submit high bids in order to get the average band price up.

All this seems a far cry from the earlier claim in an editorial in the DOE renewable energy journal *Review* in 1990, that the NFFO 'has a major advantage over initiatives in other countries in that it takes a whole range of renewable technologies capable of being applied for electricity (and) neither encourages nor discriminates against any one particular technology. All pit themselves against real market conditions'.[32] The designated bands and the various ring fences within ring fences may ensure that some projects get going, but clearly it will be at the expense of the ideal of full 'open market' competition. Step by step the government is having to abandon full competition and intervene to direct or at the least protect the development of each technology. The next logical step is to move beyond selective market protection to actual targeted investment.

That of course raises the question of *which* of the renewables should be emphasized. Currently, market criteria dominate, with wind power consequently being seen as one of the front runners along with passive solar design, micro-hydrolectric turbines and some biofuels. These *may* be the best bets, but current unit cost estimates may not be the best guide to long-term costs and benefits: there are costs associated with foreclosing options prematurely and there are other strategic and environmental factors to consider, not least the scale of the resource and the associated environmental impact. For example, on land wind could perhaps ultimately supply up to 20% or more of our electricity, but finding suitable and acceptable sites may limit it to, say, 10%. However, even though the associated unit cost may be higher, the offshore resource is much larger and is much less environmentally constrained. Similarly for deepsea wavepower.

Strategic concerns and trade-offs like this imply the need for careful assessment of priorities within an overall context of a fully developed national energy policy, this in turn reflecting wider global environmental and resource constraints. Unfortunately that is just what is missing at present in the UK – basically energy choices have been left to the market to decide, with minimum state intervention apart from a few *ad hoc* schemes. As has been suggested, this may not be sufficient for the future, in which case there could be a need for more comprehensive strategic assessment, overseen perhaps, as the Labour party has recently suggested, by a new Renewable Energy Development Agency.[33] Along with a serious, but not necessarily vast, financial committment by the state, in partnership with industry, to both develop the renewable technologies and stimulate markets for their energy, this could ensure that we could move towards the full scale deployment of an environmentally sustainable and commercially viable set of technologies.

ENVIRONMENTAL CONSTRAINTS

Of course, that is not to deny that there are likely to be problems, as with all new technologies. Quite apart from purely technical problems, renewable technologies face something of a unique challenge in being both part of a 'solution' to some gobal environmental problems (eg CO_2 emissions) and at the same time introducing some other, generally lesser, local environmental problems, eg visual intrusion in the case of wind turbines.[34] Although there may be some difficult trade-offs to make, in principle it should be possible, given time, consultation and careful design and siting, to eliminate or minimize many of these local problems. However, one of the practical problems with the current NFFO/levy contract arrangements, certainly in their first year, has been that there has been insufficient time for full local consultation and environmental assessment. In the case of wind farms, the tight contract conditions have, it seems, forced some developers to target more environmentally sensitive high wind speed areas, thus precipitating opposition from some environmental and conservation groups. However, such opposition is not always aimed just at the project. As the Campaign for the Protection of Rural Wales put it in response to a wind farm proposed on the edge of the Snowdonia National Park, while they plan to oppose any inappropriate sitting proposals, they support windpower in general and aim to 'lobby hard to amend the financial package currently on offer to developers' so as to allow less invasive siting.[35] Their conclusion that 'a much better policy and guidance for renewables is urgently needed in Britain', would seem, as we have seen, to be one shared with many developers.

CONCLUSION

In July 1988, the then Under Secretary of State for Energy, Michael Spicer, claimed that 'the climate for developing renewable energy technologies in Britain has never been more favourable; in particular privatisation of the electricity supply industry should boost the commercial prospects for these technologies as a free market is established.[36] Given that the privatization process has only recently been completed, no final conclusion can be made. However, while some improvements have been made in 1991, it seems that at least initially, neither the free market or much of a significant boost to renewables materialized.

That is not to say the NFFO is irrelevant. It has clearly helped some projects, with the 1991 outcome being clearly an advance on the 1990 round. The prospects for the future are still a little unclear. But, while to many people in the renewable energy and environmental communities, the pace still seems agonisingly slow, the NFFO/levy arrangement could in principle provide a means for the fairly rapid development and deployment of renewables, if for example the government relaxed some of the financial constraints on the NFFO contracts. If a large number of renewable projects came forward in subsequent years, following, say, the relaxation of the 1998 deadline, the NFFO levy system would provide support. However, despite the governments' insistance that the development of renewables within the NFFO/levy system is now up to the market, it still retains some control over the scale of the final statutory NFFO allocation, and it would no doubt, reasonably enough, be wary of letting the levy (and therefore the prices consumers were charged for electricity) rise too much.That sort of consideration could be lessened if there was a strategic committment, on behalf of the government, to stimulate the development of renewables rapidly via some form of direct aid on, for example, environmental grounds. But, as we have seen, that sort of committment seems to be absent or at least to exist only at a low level. In which case, given the governments' insistence that a fairly severe competitive climate must be retained, the onus for overcoming the substantial financial obstacles, and for the development of renewables generally, will fall almost entirely on the developers.

Although they have shown some interest in the NFFO, the main generation companies, NP and PowerGen, have, given the post-privatization arrangements, no direct incentive to enter the renewables field. The obligation to contract to fill the renewable quota falls only on the 12 RECs, some of whom may resent this obligation. Some REC's (like Yorkshire Electric and NORWEB) are initiating, or at least supporting, renewable generation projects, eg in conjunction with consortia like the Wind Energy Group. But the onus so far seems to be on other companies, eg the newly-privatized Water Companies and a variety of independent companies, large and small.[37] The emergence of the new NWP consortium may change the overall situation to some extent, and the expansion represented by the 1991

NFFO certainly boosted morale within the renewable energy community. Overall, while some of the smaller developers are confident that they can succeed, especially if like Ecogen they receive external financial support, for the moment the prognosis, given the ever-nearing 1998 levy cut-off date, still looks uncertain. For example, there was some concern that the relatively high band prices offered for wind projects might undermine the credibility of windpower. On this issue, the Minister, Colin Moynihan, when announcing the 1991 NFFO in November 1991, claimed that 'wind technology has some way to go before it can become commercially competitive', a view not shared by many windpower developers, who, whilst recognizing that wind power is a developing technology, would point to the economic viability of wind projects in Denmark.

The situation in the UK for windpower, and the other renewables, would hopefully change if the 1998 constraint was removed, as it may well be for the 1992 NFFO. Further ahead, there is the governmental review of policy on nuclear power and of the NFFO, scheduled for 1994 with, judging by the conclusions of the Hinkley Inquiry,[38] the strategic insurance value of 'diversity' in relation to ensuring security of supply and responding to the greenhouse global warming issue, likely to figure centrally. In this context, the nuclear industry will no doubt try to reinstate nuclear power as a key strategic option. Interestingly, there are already clear signs that, rather than its traditional hostility to renewables, the nuclear industry is beginning to welcome renewables as a stable mate, rather than a rival, within the NFFO, the 'nuclear' and 'renewable' elements of the statutory NFFO now having been formally decoupled.[39] Certainly this view seems to prevail in government, with the Secretary of State for Energy, John Wakeham, endorsing the comment in the Inspectors Report on the Hinkley Inquiry that 'renewable and nuclear generating capacity should not be regarded as competitors: both have a part to play'.[40] More recently, the chairman of Nuclear Electric, John Collier, wrote in a letter to the *Times* that nuclear and renewables were 'naural allies and I want to encourage maximum cooperation'.[41]

However, not everyone in the renewable energy community is likely to welcome the prospective embrace of the nuclear industry. After all, given that nuclear power has received the lions share of R&D funding over the years and still remains in the public sector, while renewables are having to face the market with only 2% or so of NFFO/levy as protection, the situation remains a little imbalanced. Moreover, as argued earlier, it seems unlikely that the situation will change significantly in the near future, with renewables, given the present arrangements, unable to make a very significant showing before 1994.

The advent of a new government could of course alter priorities, as could the results of the new review of renewable energy technology currently being carried out by the DOE, to update Energy Paper 55.[42] But whether or not new policy committments emerge, there would still seem to be a need to consider how support for renewables can be best organized.

As has been argued in this paper, at the very least there seems to be a need for some improvements in the NFFO contract/levy system. Beyond that, it has been argued that the present arrangements represent a somewhat half-hearted hybrid market/interventionist system, which, even if there were a 'level playing field', would still leave short-term price and market factors to shape important long-term strategic choices concerning patterns of technological development. Instead, a case has been made for a more interventionist approach, with limited, but serious public financial committment, in partnership with the new privatized ESI.[43] The specific measures that would be most appropriate would depend on the overall strategic assessment, but they would include strategically targeted operating subsidies, coupled with capital installation grants to help the less developed technologies, all within the context of fully developed national energy policy.

Parts of an early version of this paper were included in Roberts, Elliot and Houghton, *op cit*, Ref 43. Thanks are due to Marcus Rand from the Open University Energy and Environment Research Unit for comments on an early draft.

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Chapter 19

The Cinderella Options

A study of modernized renewable energy technologies Part 2 – Political and policy analysis

M.J. Grubb

Many factors contribute to the low status of renewable energy. The scepticism engendered by their apparently poor track record during the 1980s is compounded by various limitations in the available data, a reluctance or inability to project technical developments, and a failure to transfer the results of technical assessments to the policy community in ways which influence energy projections and policy. The speed and extent to which the large potential for renewables can be realized will depend upon how rapidly the resulting dismissive attitudes change, and upon policy developments in response to this. Removing existing market obstacles, increasing R&D expenditures, and various forms of support including institutional reforms can all be clearly justified, and they could make a large impact on renewable energy developments.

Keywords: Renewable energy; Energy policy process; Supply

In part 1 of this paper[1] the author reviewed renewable energy resources and technologies, and argued that the technical prospects for renewable energy were good: they could grow rapidly in importance over the next few decades to make large economic contributions to energy supply in many countries. Given this, the study asked, why do renewables feature so little in energy projections and policy?

Energy policy cannot be considered without reference to the environment. With the attacks on nuclear power now joined by the rise of concerns about the manifold impacts of fossil fuels, the potential role and impact of renewable sources – for good and bad – should be a central element of the policy debate. It is not. This paper examines some of the reasons for this state of affairs, and the policy issues which would arise from taking renewable energy sources more seriously.

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The track record

One reason for current scepticism about renewable energy is the disappointing progress made in deploying renewables during the 1980s. Programmes for promoting renewable technologies in developing countries have rarely met hopes. In developed economies, the picture has been no more encouraging. The crash US programme of the Carter years set a target of 20% renewable supply by the year 2000; the figure will probably not be half this.[2] Some other industrial countries, such as Denmark and New Zealand, also have failed to meet the hopes of earlier projections. In March 1989 the New York Times wrote that:

> Some of the biggest backers of solar energy in the US are losing interest . . . the world's largest maker of solar cells, ARCO solar, is on the auction block because the parent company . . . now believes it can put its money to better use where it has most expertise, in oil and gas . . . ARCO follows the Exxon Corporation and the Shell Oil company in leaving the solar business.

To which might be added a long list of wind and other renewable energy companies which have gone bankrupt or left the business. Things are not quite as bleak as this paints: ARCO's solar operations were taken over by Siemens, and are continuing; Shell retains some solar interests; and many of the wind companies have found private finance with which to regroup. Nevertheless it does not seem an auspicious point from which to make optimistic projections.

There are many reasons for these disappointments. The technology pushed in developing countries was often inadequate or inappropriate to the local conditions, or both. An extensive review of the US AID programme noted that 'project ideas cannot simply be transplanted from place to place . . . ';[3] this study concluded that a much greater role should be given to market forces in selecting renewable technologies. The observations also lend some support to the view expressed in Part 1, that renewable development and deployment will lead in the industrialized countries.

In the USA, a large part of the slow down can be attributed to the impact of the Reagan policies of the 1980s. These dramatically curtailed many of the Carter initiatives, with large reductions in R&D and market support for many new sources, though the impact of the latter was in some cases offset by State initiatives as in California. An excellent review of the progress of renewables in the USA noted how for every boost, there was a setback.[4] Support for renewable energy elsewhere – where it existed – was reduced as the real oil price began its slow decline from the early 1980s onwards, and then crashed in 1986.

The 1980s were a poor decade for all supply sources. World economic growth slowed, the developing countries lacked capital, and energy growth stagnated or even reversed in much of the developed world. With well-established conventional industries struggling for new business it is little surprise that novel technologies had a rough ride. The oil price collapse set them back further, and the long and deep fall of the dollar amplified the pain for foreign companies which had made renewable energy investments in the main market of the mid-1980s. Added to this was the half-hearted nature of support from many energy ministries, and in some cases more explicit market obstacles such as those outlined for the UK in Part 1,[5] and discussed elsewhere for the USA.[6]

With such a background the difficulties encountered in deploying renewables technologies to date are not suprising. Arguably, the surprising thing is not the poor record of renewable deployment, but the fact that the fledgling renewable industries have survived at all in these circumstances. The fact that some major sponsors pulled out suggests they do not expect the situation to improve as long as current conditions persist. For most purposes – wind energy in some areas being a likely exception – they are probably right.

But the current situation – low oil prices and minimal impact of environmental concerns on energy decisions – is unlikely to last. The record can explain, and in part justify, some of the scepticism about the short term prospects and the rate at which renewables could be brought onstream. But this in no way invalidates the technical conclusion drawn in Part 1, or explains the near absence of renewables from the mainstream energy–environment debate.

In directing an international project on 'Energy Policies and the Greenhouse Effect',[7] the author has discussed energy options with experts in many countries. Concerning renewables, the pattern which emerges is not only one of deep scepticism, but of widespread ignorance on many aspects of non-hydro renewable energy sources. At least four separate factors can be identified to explain the current state of affairs:

- a lack of primary data concerning some renewable energy resources and uses, which leads to an underestimate of both their actual and potential economic contribution to supplies;
- excessive conservatism in technology and resource assessments, arising in part from the unconventional nature of many renewable energy technologies and applications, and the legacy of outdated studies which reflect these same failings;
- failures in transferring existing knowledge to the policy community; and
- failures of vision in applying existing and broadly accepted assessments to energy projections and policy.

Each of these bears closer analysis.

Data gaps

The data base for assessing renewable energy resources is in many cases poor. The solar radiation resource is usually quite well known, but countries often lack adequate surveys of other resources.

Global wind maps exist, but few in the wind energy business pay much attention to them. Wind regimes are affected by a wide variety of local effects, still not fully understood. National and local wind maps often do not indicate the density of measurements, the validation procedures (if any) used for data,[8] or sometimes even the height of the measurements above ground. Detailed and careful assessments are required to determine the actual resources. Indeed, the wind speed maps for California available in the 1970s suggested that there were no areas suitable for the development of wind energy. The Californian Energy Commission Surveys, which identified the strong winds in the broad mountain pass areas, were a critical factor leading to the development of wind in California: one leading official commented that 'the wind [business] . . . could have gone elsewhere in the US, but the data were just not there.'[9] The practical wind resource in California is now estimated at around 13 000 MW.

Biomass resources from existing forest and crops wastes can be estimated crudely from existing area and turnover statistics, but often the energy potential of these has not been quantified on the basis of different possible conversion technologies. The potential from various industrial and domestic waste products, such as delineated in the UK's NORWEB/ETSU study[10] has rarely been identified. The suitability of soils and climate for different energy crops, and the consequent energy potential with existing or projected technologies, has rarely been adequately quantified.

Geothermal aquifers are mostly exploited in regions where steam breaches the surface: surveying for deeper aquifers has rarely been carried out. For hot dry rock (HDR) assessment, heat flows and/or gradients may be known in general, but often they rely on a few measurements which could miss local anomalies. More importantly, surface characteristics may give a poor guide to the temperatures 5–6km below ground which could be of primary interest for HDR,[11] and subsurface structures which might aid HDR (eg natural fracture zones) are entirely unknown. A striking indication of this occured in 1989, when a geological research well in central Europe had to be abandoned because the rock temperatures encountered quite unexpectedly proved too high for drilling to proceed to target depths.[12]

Tidal heights and offshore wave characteristics are generally very well known for shipping reasons. Promising areas for tidal energy – large estuaries or inlets with relatively narrow mouths – are usually easy to identify, but assessment of energy output and costs requires much more detailed work, including data such as depths profiles and bottom rock characteristics; estimates, if they exist at all, are usually very rough. Possibilities for enhancing tidal energy capture through resonance effects[13] have rarely been assessed. Local shoreline or other concentrations of wave energy, which could be critical in exploiting wave resources, are usually unknown except through local folklore.

The lack of data concerns not only resources, however. Most international energy statistics – and often national ones as well – report only data for energy which goes through conventional energy networks – commercial fossil fuels, nuclear, hydro, etc. Non-commercial sources, and those which involve transactions outside the main commercial energy routes (eg solar water heating, charcoal, etc) are often ignored.

This is for the simple reason that gathering such data is extremely difficult, if not impossible. Nevertheless, it does mean that the existing renewable contribution is frequently overlooked. Combined with the limited data on resources, this inevitably downgrades renewables in general energy assessments.

Analytic conservativism

It is an old saying that 'he who lives by the crystal ball will die eating ground glass'. Perhaps with this in mind, and because of the obvious difficulties and uncertainties involved in trying to project technical improvements, many assessments have tended to be very cautious in their assumptions about technology development, and the likely extent to which renewable resources could be exploited. Often indeed there seems great reluctance to project any substantive developments at all.

The problem with this of course is that technology is never static, so that assessments which assume it is are more likely than any to end up with their noses in ground glass – or simply to disappear into history. Unfortunately, the general aura of pessimism surrounding such studies tend to persist.

This is certainly the intellectual legacy of many of the major energy studies of the 1970s. For example, the IIASA study *Energy in a Finite World*[14] devoted two detailed chapters to considering the various renewable energy resources and technologies. The first noted the large physical potential for direct solar energy, but, unwilling to make projections of the young technology of photovoltaics, IIASA analysed the impact of large-scale use of centralized solar power towers.[15] The systems analysed costed many times conventional options (they still do) and used much more concrete and steel than fossil or nuclear thermal stations. Needless to say, modelling the impact of deployment of hundreds of gigawatts of this cumbersome, uneconomic and highly materials-intensive technology led to the conclusion that it would be cumbersome, uneconomic and highly materials-intensive.

IIASA's second renewable energy chapter considered the renewables other than direct solar (biomass, wind, etc). It contained substantial original research and data on renewable sources, but technological assumptions were mixed, and contained some incorrect physical assumptions.[16] IIASA foresaw a 'valuable, supporting role for these nondepletable resources', though this did not entirely reflect the technical assessment, which despite its limitations was somewhat more optimisitic than this phrase suggests.[17]

An even more striking example – because it was devoted explicitly to assessing renewable energy – was the US Technology Assessment of Solar Energy (TASE) project.[18] In keeping with the time, the introduction gave an awe-inspiring account of the breadth and depth of the expertise and analysis summarized in the final report. Apparently also in keeping with the time, the analysis adopted the peculiar assumption that the fledgling renewable technologies would remain fledgling. The exhaustive analysis concluded that forcing a host of expensive and polluting technologies[19] upon the USA would be, well, expensive and polluting. The California windfarms bear testimony to the profound wisdom of this observation, but equally, to the profound indefensibility of assuming that technologies still rooted in the nineteenth century would develop no further once the necessary resources and incentives were available.

More recent studies have for most part appeared more realistic (though it is not impossible that in another 10 years this comment too will have indigestible consequences). Indeed it is by no means always true that official assessments are pessimistic, as for example (it seems now – though it could change again) with HDR in the UK. But there are clear reasons for conservatism. Projecting technical advance requires some insight into the possibilities, unless it is to look simply like wishful thinking; it requires expertise and imagination, and some possibilities are bound to be overlooked. Of course, overlooking problems can also be important, but this tends to apply at later stages, when particular favoured technical approaches are being developed with commercial expectations. Also, unexpected problems tend to be most severe for large, complex systems.

Overall, it does seem that official assessments of renewables which with hindsight appear optimistic are in a rather small minority. It is equally true that independent assessments have often proved optimistic, at least with respect to the expected pace of development; but there is a clear case for supporting both to get a broader view of possible outcomes.

However, official and other technical assessments, especially those which try and consider explicitly the possible impact of R&D and other policy on renewable energy developments, do now seem much more optimistic than the state of the debate would suggest.[20] Inadequate data and analytic conservatism, and consequent relative ignorance concerning both present and future, are by no means the only factors.

Transfer ignorance

The factors noted above render attempts to quantify the long-term potential of renewable sources inevitably uncertain, but the situation is as much a reflection of the low status of renewable energy as a reason for it. Different kinds of ignorance contribute to this low status, of which a major part is the failure of existing knowledge to be transferred to those in the realm of energy policy analysis and formation. Wind energy affords numerous examples: the five myths dispatched in Chapter 1 survive strong and healthy in many arenas. A degree of such 'transfer ignorance' concerning the current status of developing technologies is inevitable, because information takes time to disseminate, and because some scepticism is desirable (since those involved with any technology are usually unduly optimistic about its progress and prospects). Yet the problems are deeper than this. A major factor is the sheer difficulty of translating available information into forms which can be readily understood by non-specialists.

The difficulties in summarizing conventional resources are multiplied many fold for a technology such as wind energy, for example, where: the resource is uncertain because it depends upon the practical size of machines, the required spacing between them, and the practical siting density; the costs are very variable because of the large variation in site windspeeds, siting costs, and performance; and where the value of the variable electricity generated is disputed, but certainly depends upon the size of the system and the capacity deployed.

An attempt to summarize the relevant information and uncertainties in a form which allows for some of these factors whilst remaining condensed enough to be useful to the general policy community has been attempted with the UK renewable resource table presented in Part 1 (Table 2). Currently, even if the data are available, constructing such a table requires a depth and understanding which can only be obtained from extensive study of fairly obscure and technical reports. In the current flurry of analysis concerning possible responses to the greenhouse effect, a table such as this would seem an essential tool in assessing the possible role of renewable energy; but to the author's knowledge, resource tables which attempt to reflect adequately both the potential and the uncertainties have not appeared for any other country.

As a result, the policy debate is frequently clouded by false certainties, and is often years behind technical assessments. Yet even when fairly positive assessments of renewable energy have emerged from government studies – which has happened in a number of countries in recent years (Part 1, and Ref 19 this paper) still these seem to have little impact on overall energy projections or policy. This points to the fourth and final factor considered here.

Failures of vision

The striking feature of the major energy studies of the early 1980s quoted above lies not so much in the failure to consider the paths of technology development (several studies did make reference to possible advances), but the failure to reflect adequately the possible consequences of technical developments which the discussions note as possible. Similarly, the most striking feature of the current debate is not the pessimism of technical assessment, but the low profile of renewables in projections and debate, often in sharp contrast to recent technical studies. This points to a phenomenon which might be termed a *failure of vision*.

This is not only the preserve of past studies: the phenomenon is alive and well today. Consider, as one example, the implications in Japan if any of the 'big three' technologies identified earlier are successfully developed and widely applied. First, the bulk of Japan lies below 40 degrees North and has a relatively good solar resource. Given the high energy prices arising from the lack of indigenous fossil fuels, the prospects for economic photovoltaics are better than in many other countries, initially for meeting special loads (islands, isolated houses, air-conditioning) and later for meeting baseload demand. Resource estimates vary, but go up to very high numbers, according to siting assumptions.[21] With successful development of the technology and time enough, photovoltaics might even be able to generate as much as the power system could utilize, which would be considerable.[22]

Second, Japan still has large forests, and significant agricultural wastes, including wastes from forest industries. Wastes might yield up to nearly 20 mtoe/year, or around 100 TWh/year of electricity. If forest residues and crops can be converted to electricity at high efficiency this figure might in principle be quadrupled,[23] though this might entail considerable land conflicts. Such biomass use would also make the system able to absorb more PV output.

Third, Japan lies on the Pacific 'Ring of Fire'. Japan's experimental HDR well reached a reported temperature of 180°C at 2km, less than half the depth required to reach such temperatures at the best sites in Britain. Much of the country – including a large region around the Tokyo–Osaka corridor – has heat gradients which are very high by international standards, according to preliminary studies published by NEDO.[24] The gross resource must be unquantifiably large. The practical potential is a matter of conjecture, but it is striking that if the economic assessments made by the UK ETSU team in 1986[25] had been applied to the Japanese resources, the conclusion would have been that Japan's hot rocks could provide an almost infinite source of electricity more cheaply than anything else available.

Japan is a country synonymous with energy resource poverty, and is quite densely populated, but it seems that Japan could meet much or all of its electricity needs if all of the 'big three' infant renewables were successfully developed to the point of large-scale commercial feasibility. That of course is unlikely, but it seems equally unrealistic to assume that *none* of them will be. Yet, less than 6% of Japanese government direct energy R&D expenditure goes to renewable technologies (more than half of this goes on photovoltaics). More striking still, in the deluge of Japanese literature examining possible responses to the greenhouse effect, there has been relatively little mention of renewable energy. Indeed, there has been more discussion of, and may soon be more money devoted to, ways of trying to remove and dispose of carbon from fossil fuel power stations, though most of the technologies are far more speculative even than those for HDR.

If all this were based upon extensive studies which demonstrated basic physical reasons why these technologies were unlikely ever to become viable, this would be understandable. Yet such studies do not exist. This example is chosen because Japan is not exactly known for missing technological opportunities; if it can happen in Japan, it can happen anywhere. And it does.

It is important to emphasize that the problem is not primarily one of specialist technical assessment. Japan's NEDO has noted the large potential for renewable energy; most of the estimates of UK renewables discussed in Part 1 are based on studies by the Department of Energy's ETSU. Estimates of possible future contributions published by the CEGB and Department of Energy itself are much smaller than the estimates of overall resources discussed in Part 1 (because of limited time horizons and/or more pessimistic siting assumptions) but are nevertheless far from insignificant.[26]

The divide lies more between the technical assessors and the general energy policy and political communities. The idea that non-hydro renewable sources might, on foreseeable timescales, contribute substantially to energy supplies in industrialized countries seems to be so far from the conventional wisdom that information indicating this is often discounted. The scepticism born of past disappointments is compounded by the historical focus on large centralized systems which makes it very hard to conceive of major supplies being gained from many relatively small, dispersed inputs, which are typical of many important renewables. The gap between perceived and actual potential is, in the author's view, growing dangerously wide. Technological advances, and in some cases breakthroughs, are certainly needed: but the revolution required is one of attitudes.

Whither the debate?

It has been argued that wide information and perception gaps exist with respect to renewable energy. Why do these persist and how might the gaps narrow? Obviously, there are elements of vested interest seeking to protect existing industries from potential competition, and political interests seeking to defend past decisions about major resource allocations in the energy sector. Scepticism born of past disappointments is a factor; so is the emotional attachment of many physicists and engineers to large and centralized power sources, especially nuclear power. Yet in themselves these explanations seem inadequate. To throw more light on the situation it seems necessary to turn more to the realm of social sciences. It is now nearly 30 years since Thomas Kuhn published one of the most famous books on the philosophy of science, *The Structure of Scientific Revolutions*,[27] which examined the way in which the major theoretical scientific advances had occured in practice. The analysis – rarely disputed – demonstrated that such 'scientific revolutions' rarely followed a smooth progression of ideas, with those in the field gradually modifying their views in keeping with new evidence. On the contrary, science and other disciplines reside in established paradigms – the dominant ways of looking at and interpreting data: for example, the earth-centred universe, the Renaissance theories of burning ('phlogiston theory'), or Newtonian mechanics. 'Scientific revolutions' were characterized by periods of growing tension, dissent and confusion, in which accumulating evidence which appeared to conflict with the dominant paradigm was marginalized, ignored, or even abused. The emergence of a new paradigm, which could make better sense of existing data, was fiercely resisted – whether it was the Copernican heresy, Lavoisier's oxygen, or quantum mechanics.

The current situation with renewable energy sources, in the author's view, displays some remarkable parallels with the structure of such scientific revolutions. The dominant paradigm, as displayed by official forecasts and statements, R&D funding, market supports, and national and international institutions, is that fututure energy supply in industrial countries will necessarily remain dominated by large centralized fossil, nuclear and hydro resources. This paradigm faces growing tensions. Projected fossil fuel use is probably inconsistent with resource and/or environmental limits (or, to be more precise, the economic and environmental costs of extraction on such a scale appear so high that alternatives will necessarily come to the fore). The nuclear faith is increasingly at odds with institutional, political and economic trends in most countries. Statements on renewables made from within this paradigm frequently apply unrealistic criteria to immature technologies, involve inconsistent treatment of the importance of 'public acceptability', and in some cases involve factual distortions.

This is leading to a massive energy/environmental impasse, in the shriller forms of which one side is accused of promoting environmental devastation whilst the other is accused of seeking to destroy economies. Accusations of bad faith and sharply conflicting assessments of impacts and alternatives abound.

The converse is not to deify renewable energy, which still faces obvious technical uncertainties and other difficulties, including environmental impacts; some renewable assessments reach indefensible heights of optimism and simplification which is just as misleading as outright rejection. Some of the tensions can be lessened if more serious assessments of renewable sources are brought into the picture, but on neither side has a reasonably objective and informed assessment of renewable energy featured strongly. So where does the debate go from here?

In the author's view, the existing paradigm can no longer be plausibly defended against the technical developments in renewable energy. However, the question is not merely when the paradigm will collapse – that will be a many-staged and ill-defined process, which indeed is already beginning. The more serious questions are how, and what will arise in its place?

The second of these can be answered reasonably easily. Renewable energy resources cannot meet unlimited needs: the density of demand for electricity alone in some of the more densely populated industrialized countries may already push at or exceed the limits of what seems practical for renewable supply, even if major technological advances do occur. Electricity is the energy carrier which is by far the best-endowed with renewable resources, excepting low-grade heat in some areas, and it is hard to foresee renewable alternatives to some current fossil energy applications. Therefore for renewables to make a large impact, efficiency in energy use is essential, and even then the 'problem within the problem' of fossil fuels for transport and some special industrial applications remain.

The only renewable technologies which seem relevant in these sectors are liquid fuels from biomass and hydrogen from PV. At least in countries with high population densities like much of Europe and Asia, liquid fuels from biomass seem likely to remain fairly minor compared with needs. Hydrogen from PV is still speculative, and for equally good reasons it seems improbable that costs could compete with natural gas until there are very large gas price rises. Indeed without such price rises, natural, methanol or fuel-cell gas itself would be a better bet for breaching the transport barrier, through compressed natural gas cars. Also, the infrastructural requirements for an international solar hydrogen economy are so vast that it would take many decades to become established whatever breakthroughs occurred.

Added to this is the fact that deployment of large-scale renewable energy will have many environmental impacts. Biomass use can involve large land-use changes. Waste combustion can result in various emissions. Tidal barrages change the tidal regime in estuaries. Wind farms have a large visual impact. Geothermal stations would bring large volumes of minerals, some in toxic quantities, to the surface. PV manufacture still involves toxic chemicals. Even offshore wind and wave systems would have seabed and perhaps other unknown impacts. Indeed, IIASA considered that large-scale renewables would involve undertaking 'ecological management of awesome scale';[28] an exaggeration, but a pointed one.

In other words, renewable sources cannot possibly be a panacea for all our energy woes. What they probably can do, however, is to form the third leg of a triad of responses which will form the path out of the current energy/environmental impasse: efficiency, gas, and renewables. Other resources – coal, gas and nuclear in the countries which choose this option – will remain important. But they will not dominate in the way they have in the past, or in the way most projections see for the future. This, in the author's view, will be the paradigm which emerges to become conventional wisdom. The probable role of gas is already acknowledged, and on the path. Efficiency is now established as a core component of the debate. A revolution in attitudes towards renewable sources will complete the picture.

The path towards this could lie somewhere between two extremes. On one model, official projections could continue to marginalize the possible renewable energy contribution, and funding could remain pitiful. The major uncertainities, both technical and environmental, would remain unresolved. Environmental groups could continue to assume that all the technologies could be successfully developed, given the financial support, and ignore the possible environmental implications of large-scale renewable systems.

This is barely a caricature of the present situation. However, the energy/environmental conflict is likely to sharpen further. Antipathy towards nuclear power shows no sign of abating, and in most of the countries still following the nuclear path it seems to be growing. Acid rain and tropospheric ozone are still broadening problems. The evidence for greenhouse warming seems increasingly strong, and a train of floods and/or severe droughts would generate enormous political pressures. Even without that, environmental concerns seem set to deepen.

Undoubtedly, there are many who see in this looming crisis the prospects of a nuclear revival, which taking renewables more seriously might threaten. The problem is that *not* taking renewables seriously could pose an equal or greater threat. The renewables debate is bound to grow, and starving it of the technical and deployment experience needed to make realistic judgements will leave proponents free to elaborate conspiracy theories about the suppression of painless alternatives to nuclear power. This could damage nuclear prospects just as much as taking renewables seriously, but in a far more destructive way, with deep societal divisions and wild swings of policy in the offing.

This indeed could be the situation building up in Sweden, where the probable attempts to abandon the nuclear phaseout at some stage in the face of supply shortages will inevitably be met by accusations that the renewable alternatives, primarily biomass gasification and windpower have never been seriously tried. And such accusations would not be without some foundation: given the situation, the resources devoted to developing the main renewable energy options in Sweden seem seriously inadequate.[29] Unless there are some very rapid changes, the model of the consensus society could degenerate into a prototype for the next round of energy/environmental conflicts.

At the opposite extreme, on a cooperative model governments could soon accept the possible potential for renewable sources in their projections, and the implications of this in terms of policy, which are discussed later. For their part, environmental groups would need to face some unpleasant facts. As noted, development of large-scale renewables would not be without technical disappointments and environmental impacts. To date environmental groups have displayed at best mixed attitudes to developments of hydro, tidal power, and in some cases waste combustion and wind developments. When renewable technologies move from development to deployment, a number of environmental trade-offs will have to be made. Sustainable development in the energy sector can mean many things, but it will certainly not mean invisible development, and environmental groups will have to accommodate this reality. It is indeed possible that, when faced with the realities of large-scale renewable energy, societies will become more favourable towards nuclear power, and negotiate conditions for a nuclear revival.

The 'cooperative' path would not be easy. It faces a triple inertia, with that of intellect being reinforced by those of existing institutions and investments. But some moves towards this are quite possible, and another set of issues then arise. If attitudes did change, renewables did feature more seriously in energy projections, and governments did seek ways to encourage large-scale developments – what could they actually do?

Broadly, there seem to be four main policy areas that need consideration: removing market obstacles; R&D; support for deployment; and institutional reforms. The rest of this paper considers these in turn.

Removing market obstacles

Chapter 1 noted that some renewable energy options appear to be economic already, even at current energy prices, but were not being pursued. This is reminiscent of the 'energy efficiency gap' – the fact that many cost-effective opportunities exist for improving efficiency which are not being exploited. Many reasons for this situation have been advanced; the main ones were summarized recently in *Energy Policy*.[30] Concerning renewables, some of the same issues apply.

One factor is information. Particularly for renewables which 'ride on the back' of other activities, such as energy-from-waste, publicity concerning the basic technical opportunities is important because people may simply be unaware of the opportunities. Information has been one of the most widely recognized, and widely met, needs in recent years, perhaps especially in countries with governments which are wary of more direct forms of intervention.

Information needs can be more onerous. The example of wind energy, where the real windspeed at 20–30m above ground level over various terrain is often quite speculative, has already been noted. The costs to small-scale developers of measuring winds at many different potential sites, starting from little, may be prohibitive. Broader assessments of the wind characteristics in different regions, carried out by governments and available to all, would be an important boost.

Incentive problems often arise for the more disaggregated renewables. This is most obvious with respect to passive solar heating. Since this needs to be incorporated into building design, it depends upon architects being both knowledgeable and motivated to incorporate solar features. Since the economic benefits are rarely passed on in terms of house prices, the incentives are small or non-existent. Passive solar depends primarily upon architectural training and upon guidelines in building regulations.

The obstacles to active solar systems for heating water also share much in common with building efficiency issues; deployment requires expertise and incentives at the household level. Because of high consumer discount rates, and the fact that many buildings are occupied by people who do not own them and/or who expect to move after a few years, the 'market' can capture only a small fraction of the economic potential. The importance of government policy is indicated by the wide variation in takeup between countries of similar climates – 60% of buildings in Israel use solar water heating, for example, compared with little or none in some equally sunny countries. Clearly, government incentives or regulations, often of a similar form to some of those required for promoting efficiency, are crucial to the deployment of these and other household-level renewables.

Similar remarks apply to some opportunities for exploiting agricultural wastes, particularly from small farms. Turning from wastes to actual energy crops raises two special issues. One concerns the extent of existing agricultural subsidies, and the 'problem' of excess agricultural land. A US report estimated that over the next 25 years new uses would have to be found for 60 million hectares of agricultural land,[31] which on typical assumptions of biomass yields might yield around 5% of current US primary energy. New uses are also sought for land in the EC; one study estimated that a major move of the EC agricultural subsidies and excess agricultural land towards biomass energy could result in EC-12 crops generating up to 100 mtoe/year by the year 2010, up to 10% of EC energy.[32] Agricultural subsidies and land-use are, of course, major political issues, but the possibility of transferring a portion of them to energy does not even seem to have featured significantly in the debate.

The second special feature of biomass is that it represents accumulated carbon. With all the discussion of the greenhouse effect in general, and carbon taxes in particular (considered below) the benefits from absorbing carbon while forest crops are established may not be insignificant. It is also possible that after reaching a steady state, they would continue to fix a small amount of carbon in the soil. Direct carbon credits to reflect this could tip the balance in favour of quite substantial energy crops.

Some renewable sources face specific legal and tax impediments. In the UK for example, micro-hydro schemes which have an energy cost half that of conventional power are rendered uneconomic by the charges levied for 'use' of the water; regulations in the USA have similarly rendered micro-hydro development almost impossible, and some other renewables face other idiosyncratic obstacles.[33] These include, in some countries, large-scale existing supports for conventional sources, as in the USA where the first plea of the renewable energy community is not for subsidies but for a 'level playing field'.[34]

However, probably the most important market obstacle lies in the nature of utilities as they currently exist in most countries. Development of many renewables requires detailed local understanding of conditions, and may be associated directly with other developments – for example, biomass from agricultural or forestry wastes, or for using marginal farmlands; use of domestic wastes directly or in landfills; wind developments on hillslopes used for cattle farming; and perhaps in the future PV integrated into the design of commercial buildings. It is very difficult if not impossible for large centralized utilities to manage such developments even if they want to. Most would have to be developed by independent producers, selling excess power to the grid. The ability to do this, and the terms on which it is done, will therefore be crucial in determining renewable energy developments. This is essentially a matter of utility regulation.

The central place of the PURPA regulations in wind energy was noted in Part 1; Sawyer[35] notes the 'glacial' pace at which PURPA was implemented in most other States as a key reason why California led these developments, in addition to the Commission's resource surveys.

Changing the market for renewables in these ways could have a large impact for those renewables which are quite well developed and predominantly small-scale. Yet as noted, renewables from a very diverse group which include poorly developed technologies and large-scale, capital intensive forms. These factors raise a number of more familiar policy issues.

Research and development

The first cry of supporters of renewable energy – and many other energy sources – is for more government expenditure on R&D. The basic justification for R&D expenditure in a market economy are simple enough. Companies work on too short a timescale to invest in long-term technology; they are unwilling to take the scale of investments and uncertainties involved; and they would often not be able to obtain the full returns on R&D because some basic industrial processes cannot (and should not) be patented.

Because of the nature of the uncertainities in technology development, there has to be a degree of balance across a wide range of technical avenues. As indicated in Part 1, this has not been a feature of energy R&D, which has been dominated by support for nuclear power first, and fossil fuels second. Concerning the greenhouse effect, a common theme of official assessments has been that the world is not technically equipped to limit carbon emissions.[36] The natural corollary is that the case for increased renewable energy R&D is strong.

There are several valid concerns about R&D expenditures, as discussed below, but it is appropriate to deal with one of the more bizarre concerns first. It is sometimes said that renewable energy funding should not be increased because there is nothing usefully to spend the money on. Any potential sponsoring agencies that have money but lack ideas might like to consider the following list of items which in the author's judgement have not yet been carried out to nearly the extent justified.

- *Resource surveys*. Small-scale hydro; wind regimes, onshore and offshore; agricultural waste resources and soil characteristics for energy crops; geothermal heat gradients, rock and aquifer characteristics; localized wave climates; seabed characteristics for potential tidal barrages.

- *Fundamental research.* Various aspects of solid state physics relevant to photovoltaics;[37] power electronics for reliable and cheap interfacing of DC and small-scale variable power sources with grid systems; geothermal stress and fracture modelling for HDR; genetic and field research for improving biomass crops; some biomass conversion chemistry; computer and physical modelling of tidal estuary resonance effects and wave loads on various possible wave energy systems and offshore foundation structures.
- *Technology development.* Biomass conversion processes, especially continuous (as opposed to the better understood batch) liquid fuel processes, and electricity from gasifer–gas turbine systems; photovoltaic module development and experimentation with different siting possibilities (eg glazing); wind turbines, especially variable speed and vertical axis machines; test HDR wells at practical operating depths; hygroscopic solar systems; various wave devices in lake and then (if promising) open sea conditions; prototype offshore wind systems.

It is of course highly uncertain how much money would be required to explore such R&D issues fully. Some of the items above could clearly be quite cheap, even in the order of a few hundred thousand pounds for university based desk studies, and field surveys of resources. Potential costs become higher as one moves towards technology development. Substantive new research in wind turbines is likely to cost several tens of millions, partly because the industry is large enough to explore anything cheaper (though joint funding can still be important on smaller work). Earlier stages of trial wave systems, and photovaltic process developments, might involve similar amounts. The costs of developing an integrated biomass gasification–gas turbine system has been estimated at around US$100 million; a serious programme to develop and demonstrate large offshore wind systems could be of the same order. Programmes involving full-scale prototypes of offshore wave and geothermal HDR systems might be more expensive, running to several hundred million pounds. These refer to specific projects: internationally, and if many different avenues were explored, the figures would of course increase substantially.

Most of these numbers are quite large compared with current government expenditures on any specific renewable energy projects. Yet the striking thing about them is that, with the possible exception of major wave and HDR prototype programmes, they are modest compared with the resources devoted to some other areas of energy research (see Part 1), and wholly insignificant in comparison with the aggregate turnover of energy businesses.[38]

However, care is clearly needed. Energy R&D expenditure has a poor track record. Governments have devoted enormous resources to nuclear power, but in many countries the returns now seem likely to be far less than originally envisaged, and fusion and fast breeder reactor research may never bear useful fruit. President Carter's response to the oil price shock involved devoting large sums to the development of technologies for synthetic fuels from coal; it is now clear that these are unlikely to be of commercial interest without spectacular oil price rises, and furthermore synfuels have the dubious distinction of involving carbon emissions far higher even than from coal.

Even renewable energy expenditure has, some critics say, been wrongly focused and has yielded little; for example, wind energy programmes focused on very large machines, yet the successful commercial designs evolved from small-scale technologies under the influence of tax credits. It is by definition impossible to ensure success from R&D but nevertheless this record seems a poor basis from which to recommend new programmes without establishing the nature of the problems, and how they might be minimized.

One issue is timing. Technology development needs time as well as money: time to develop expertise, and time to learn from mistakes. Large amounts were spent in the USA under Carter, but the growth was too rapid for scientists to use the money well, and there was little chance for the programmes to bear fruit before the Reagan administration slashed renewable R&D budgets in the early 1980s. A similar phenomon occured with the UK wave energy programme, where even some supporters say that the funding was too much, too fast, only for the whole programme to be cut because of its perceived lack of progress relative to the money spent. R&D money needs stability.

Yet the danger in stability is that it can lead to complacency and continued funding of genuinely unpromising technologies. Good R&D management is required, lest easy handouts simply lead to a herd of 'white elephants' charging along under the environmental banner.

There are inherent institutional problems in managing R&D. One is that expenditure is most likely to go to projects backed by lobbies with existing political experience and influence, but these may not offer the best options. Another is that those with the best knowledge of a technology are usually those involved with the programme, and so have a vested interest in seeing that the R&D programmes continue. It is also politically difficult to terminate programmes, which may be seen to involve admission to mistakes.

All this points to the need for strong independent oversight of R&D programmes, with a mandate to obtain all available details on the technology and assessments provided by those involved. Assessments also need to be grounded in some consistent framework, which has often been remarkably absent. Yet quite powerful techniques do exist, including probabilistic techniques for assessing payoffs under a very wide range of possible future conditions.[39] Such techniques cannot give 'the answer', but they can at least encourage a broader approach to thinking about R&D, and highlight key uncertainities. A further option is to try and involve resources from private industry, even if only as very minor partners, as long as it does not compromise the availability of the primary results; corporations are unlikely to stay with a project if they conclude that it really has no signficant prospects.

Despite the failures, successful R&D management is clearly possible, and this has been demonstrated for renewables by the European Commission's non-nuclear 'Joule' programme, which independent evaluation judged to be a considerable technical success.[40] However, R&D covers only the initial stages of bringing technologies to large-scale deployment. As the Joule assessment itself emphasized, the later stages also require consideration.

Supporting the deployment of renewable sources

The rationales for supporting the deployment of new sources are simple. First, they have several advantages over conventional sources which current markets rarely reflect. Sawyer summarized the benefits concisely:[41]

> There is a basis for the passion and advocacy . . . appropriately selected renewable energy technologies conserve irreplaceable fossil fuels, reduce intergenerational and international inequities in consumption, reduce the nation's vulnerability to future oil embargoes, make individual regions and communities more self-sufficient, and reduce environmental degradation.

The last of these benefits has risen in prominence and clearly could form a list on its own. However, in common with some of the other items, it reflects primarily the disbenefits of fossil fuels, rather than inherent benefits of renewables. Economically the most efficient approach in such a case is to tax the undesirable activities, rather than subsidise the alternatives; carbon taxes are an obvious example. In principle this should be an important component – perhaps the main component – in supporting the deployment of renewable sources. However, politically such taxes seem a very long way off, and more direct and specific support for alternatives seems the obvious surrogate.

In addition, all new sources face many obstacles, including various entry barriers of scale and more direct wielding of market power by established interests. Indeed as noted above, existing sources may themselves be heavily subsidized in some countries.

What kind of support might be appropriate? Two major forms can be considered. One is to define *target levels* of deployment for specific technologies. The other is to offer subsidies.

Guaranteed deployment targets ensure that a market for a new technology exists and can thus ensure investment in it, almost irrespective of costs. This has both advantages and disadvantages: it can promote technologies which are seriously uneconomic, and in some forms, the real costs involved may remain obscure; but it does at least ensure that some attempt is made, and the total costs are limited by the size of the target.

Deployment subsidies, unless very large, place a far greater emphasis on technologies which are nearly economic, and are thus less good at stimulating more speculative or risky technologies. They are less likely to shield 'white elephants' but if policies rely on moderate subsidies alone this many result in the technological equivalent of throwing out the baby with the bathwater. Also, paradoxically, the total costs of a subsidies programme may be more uncertain than with deployment targets – a very large response can result in a large payout.

Perhaps the best approach lies in a combination of the two, as for example used in Denmark and the Netherlands for promoting wind energy. A set of deployment targets sufficient to stimulate development of a serious industry were set, and the governments specified both utility subtargets and offered subsidies for private developments which were judged sufficient to ensure the near-term targets were met. The costs of the programme, and the incentive to efficiency, remains clear, but the stimulus has still been strong enough to establish new industries. Denmark is now established as the world's leading manufacturer of wind turbines, and domestic subsidies have been withdrawn on the grounds that it can now compete unaided given the relatively strong winds and high electricity prices in Denmark; in the Netherlands, with different conditions, subsidies remain a necessary part of reaching the targets at current energy prices.

However, like R&D, many programmes of subsidies and targets have less favourable outcomes. Often, similar factors are involved to those which make control of R&D difficult. In countries with strong lobbying structures, subsidies tend to go to industries which can lobby hardest, which rarely correspond with the real needs. In addition, subsidies tend to be easier to offer than to withdraw, leading to what might be termed the 'banana' problem after the parallel drawn by Nordhaus with a youngster's grammatical difficulties: 'I know how to spell it but I don't know when to stop'.[42]

As for R&D, there are no magical solutions to this, other than to define the reasons for support very clearly and to place greater emphasis on some form of independent oversight of deployment incentive schemes. This problem as a whole adds further to the rationale for using fuel taxes as far as possible to reflect external impacts, to minimize possible justifications for wide-ranging subsidies for technologies vaguely related to the overall objective of environmental improvements.

However, there remains an important respect in which government support may be required irrespective of the development of a technology and the scale of any environmental taxes, namely 'infrastructure' funding for long-term, capital-intensive projects. Most private industry operates on timescales much shorter than can be justified for decisions affecting society overall, especially concerning many environmental issues. The problem of this 'payback gap' is endemic, but reaches extreme proportions in two cases.

One is the funding of capital-intensive goods in developing countries, of which many renewables are examples *par excellence*. This is a fundamental obstacle. Given the acute shortage of capital, and very short-term perspective, throughout the economy of most developing countries, it is plain that the vision of solving global environmental problems by fuelling development with renewables will remain a mirage, unless capital is made specially available to get these sources in place in countries where the primary concern is with procuring enough energy over the next week, rather than for the next century. Since developing country governments are also often under intense pressure concerning the resources they have, they are hardly likely to promote technology with 10 year payback when less capital intensive and more familiar options – such as strip mining or oil imports – are available.

The second issue in which the payback gap reaches extreme proportions concerns very long-term projects. The most striking case is that of tidal power. No combination of fossil fuel taxes and incentives could make the largest schemes in the UK commercially attractive, because the timescales are too long and the schemes too large. Yet the benefits, in terms of providing large volumes of low-cost, pollution-free power for many decades, could be very high. Treated as a long-term development of national infrastructure, and funded at treasury rates, some large tidal schemes would be hard to beat. As a commercial decision for short-term payback they are non-starters.

Institutional reforms

In reality, not much of this is likely to happen as long as renewables remain an afterthought in energy policy, with sponsorship intended partly to satisfy public relations, as is the situation in not a few countries at present. Changing attitudes towards renewables would change much, but renewables would still be struggling against a strong institutional imbalance.

At the national level, there is a need for some kind of body which is responsible not only for technical assessments, but for understanding and overseeing the needs of renewable development and deployment. Such a body would need to be of sufficient weight that it could represent renewable energy interests effectively within the processes leading to major energy policy decisions, such as the development of utility ownership and regulation; and indeed of high enough standing that it could input into other spheres, such as agricultural policy.

At the international level, the current void cannot persist. Whether a renewable agency forms an independent group within the IEA, or is an entirely separate creation such as the IAEA and other nuclear agencies, is not as important as its status. There is a crying need for some international focus which can channel some of the large existing energy development funds towards international renewable energy projects, which can improve coordination of national R&D programmes, and which is in a position to protect and encourage renewable energy internationally against the weight of the existing international nuclear and fossil fuel institutions.

These needs will become all the more pressing as and when modernized renewables really move into the big league.

Conclusions

The principal observations and conclusions from this and the previous paper can be summarized as follows. Renewable resources are very large, and the technologies for exploiting them span a very diverse range in terms of scale, stage of development, and development requirements. This is nothing new, though it seems often forgotten. However, traditional renewables are too costly to compete against conventional fuels and usually too inefficient to contribute much to demand densities in modern societies. The success of renewable energy depends critically upon the application of modern technologies. With this the potential for large-scale economic supply from renewable sources appears to be good for many countries: it seems quite feasible for the UK to meet 25–50% of current electricity demand from relatively confident renewable technologies.

Three infant technologies stand out as having the potential to make large contributions globally: photovoltaics, modernized biomass, and geothermal HDR. None of these are adequately developed at present but the prospects for at least one and probably two are good. Wind energy stands out as a fourth technology with a big global potential, which is more developed – adolescent rather than infant – and many other renewables could be of considerable local importance. On this basis, the contribution from renewable sources globally is likely to grow rather than diminish, but in very different forms from traditional uses. Given time, they could make very large contributions to global energy supplies.

Development and deployment of modernized renewable sources is likely to be led in the industrialized world. It is the industrialized countries which have the technological capabilities, the capital resources, the infrastructure – and are most conscious of the environmental imperatives. Application in most developing countries would depend strongly on foreign finance, because of the capital and other requirements of many modernized renewables.

These conclusions are in sharp contrast to the dominant attitudes in energy policy, projections, and mainstream debate, in which renewable energy is peripheral. There are many reasons for this. The available data on both resources and existing uses are often inadequate; technical assessments are frequently conservative in their assumptions concerning technology and resources; there are great difficulties in transferring existing technical knowledge to the policy community; and there is an apparent inability to acknowledge the profound implications of possible technical successes in mainstream energy forecasts and policy development.

Taking renewables much more seriously would have considerable policy implications, for government policy may largely determine the pace of progress in renewable energy. The first priority would be to remove existing market obstacles. More extensive R&D, if carefully managed, remains important. Extensive measures to promote the deployment of renewable energy could clearly be justified, especially if environmental concerns are not adequately reflected in energy prices. Parallel institutional reforms would also be required.

None of this will be easy, either for governments or indeed for environmental groups. Resistance to new developments will apply equally to renewble sources, and substantial political and environmental battles over deployment are likely, which could only be resolved by increasing acceptance of the need for trade-offs. Promoting renewables will require major decisions taken in the face of uncertain payoffs. And the climax of this path would not be a renewable Utopia, but simply be a situation in which the technical and environmental parameters were broadly known and accepted, instead of remaining in the realm of speculation and dispute due to lack of data and experience, and in which the many renewable sources, with all their pros and cons, could be considered on an equal footing with conventional options.

Renewable energy sources cannot provide a painless solution: their contribution in some sectors is clearly limited, and they also will have environmental impacts. However, along with energy efficiency and natural gas they can help to form the path out of the growing energy/environmental impasse. The timing and manner in which these changes occur will have profound implications for energy developments worldwide.

Many people have offered comments on drafts of this paper; particular thanks are due to David Hall and Richard Shock for detailed remarks. The usual disclaimer applies.

[1]M.J. Grubb, 'The Cinderella options: a study of modernized renewable energy technologies. Part 1: a technical assessment', *Energy Policy*, Vol 18, No 6, July/August 1990, pp 525–542. Since completing Part 1, the author has had two papers accepted for publication which give technical background to the assessments of Part 1; 'The value of variable sources on power systems', *IEE Proceedings Part C*, IEE, forthcoming; and 'Wind energy in Britain and Europe: how much, how fast?', *Energy Exploration and Exploitation*, Multi-Science, forthcoming.
[2]US DoE, *Long Range Energy Projections to 2010*, DoE/PE-0082, Washington, DC, forecasts renewables contributing 9.5%

of US energy supply by 2000 and 12% in 2010, compared with 7.6% at present – despite lowered demand projections.

[3]US AID Office of Energy, 'New direction for AID renewable energy activity', Report No 88-01, 1988.

[4]S.W. Sawyer, *Renewable Energy: Progress, Prospects*, Association of American Geographers, Washington, DC, USA, 1986.

[5]Part 1 reflected some optimism that reforms during 1990, notably electricity privatization, would greatly improve the prospects for renewables in the UK. This optimisim has turned to widespread despondency, with legislation now restricting contracts under the non-fossil provisions to 8-years, which is inadequate to repay any renewable energy developments, and with financiers reluctant to fund developments without longer term contracts.

[6]*Ibid*.

[7]M.J. Grubb, *Energy Policies and the Greenhouse Effect, Volume 1: Policy Appraisal*, Dartmouth/Gower, to be published October 1990; M.J. Grubb, ed, *Volume 2: Country Studies and Technical Options*, Dartmouth/Gower, forthcoming 1991.

[8]Wind measurement is subject to many vagaries. Quite apart from anemometer inaccuracies, local interference often affects readings. Windspeed records declining over time are often due to the growth of nearby trees. A low windspeed area in Kenyan wind maps covering hundreds of square kilometres was eventually found to be due to a single partially sheltered anemometer.

[9]Ros Davidson, 'The California covenant', *Windpower Monthly*, July 1989.

[10]ETSU/NORWEB, *Prospects for Renewable Energy in the NORWEB Area*, ESTU, Harwell, Essex, UK, 1989.

[11]Some of the best areas may be where hot rocks – from magnetic or granitic intrusions – are covered by 1–2 kilometres of sedimentary rock, which usually has lower conductivity and heat flow and which consequently help to trap the heat.

[12]*Nature*, Vol 341, No 6241, p 391, 5 October 1989.

[13]I. Robinson, 'Surges in tidal power basins – can they increase power output', *Proc BHRSA 2nd International Conference on Wave and Tidal Energy*, 1981; N. Birkett, B. Count and N. Nichols, 'Optimal control problems in tidal power', *Water Power and Dam Construction*, January 1984.

[14]J. Andere, W. Haefele, N. Nakicenovic and A. McDonald, *Energy in a Finite World*, Summary report of IIASA, Global Energy Studies Project, Ballinger, Cambridge, MA, USA, 1981.

[15]Solar power towers consist of large arrays of mirrors reflecting on to a central tower, where heat is raised to generate steam. It now appears one of the least promising solar technologies.

[16]Concerning wind, IIASA (*op cit*, Ref 14) assumed extremely large machines which few now think would be practical, but also assumed that capture of winds at coasts would create a several hundred kilometre zone of low windspeeds behind it. In fact, extracted wind energy is rapidly replaced by transfer from the upper atmosphere. Geothermal HDR and other speculative geothermal sources were not included because of the technical uncertainties. The assumed global tidal resource was only seven times that of the currently-assessed UK potential. Biomass in developing countries was not included in the IIASA analysis.

[17]Overall the IIASA (*op cit*, Ref 14) conclusions were somewhat ambiguous, if not contradictory. The renewables chapter stated that 'collectively, the potential of renewable energy sources is comparable to that of fossil resources, of solar energy, and of nuclear power in 2030, although it does not grow in the period after 2030 in the way that the nuclear and solar potentials do' (p 95).

[18]Y. Schiffman and G. D'Alessio, *Limits to Solar and Biomass Energy Growth*, Lexington Books, MA, USA, 1983.

[19]The biomass technologies assessed (*Ibid*) had high emissions of various pollutants; photovoltaic manufacture involved large quantities of toxic chemicals; the wind turbines were inefficient and ugly.

[20]See various citations in Part 1. After completing Part 1, the author received a recent inter-laboratory assessment for the US Department of Energy. It concluded that the current contribution of renewables in the US is 8% of supply and is 'certain to grow' in both absolute and relative terms, and that Federal support will have a great influence on the rate of increase of the renewable market share. The 'business as usual' projection suggested 19 quads (quad = 10^{15}Btu) by 2030; with an intensified programme, the maximum projection for 2030 was 40 quads, compared with current demand of 80 quads and projected 2030 demand of 144 quads. In addition, 'the overall projection of the contribution of renewables is neither a maximum potential, nor does it require success in all technological pathways. Final, it is our opinion that renewable energy will supply additional energy after 2030 as technological progress continues and institutional constraints are overcome' (Office of Policy, Planning and Analysis, 'The potential of renewable energy – an interlaboratory analytic paper', US DoE, Washington, October 1989).

[21]Cited in A. Tanabe, 'A case study of Japan', in Grubb *et al, op cit*, Ref 7.

[22]Japan currently generates about 83 TWh/year from hydro stations, and resources could allow up to 50 TWh/year more (*Ibid*). The southern areas, representing the bulk of demand, have peak demand in the summer. Both factors tend to aid the integration of photovoltaics.

[23]Tanabe, *op cit*, Ref 21.

[24]New Energy Development Organisation, 'The map of prospective geothermal fields in Japan', NEDO, Tokyo, 1984.

[25]R.J. Taylor, 'The 1987/88 geothermal HDR programme review', Energy Technology Support Unit, ETSU R-46, Harwell, UK, 1988.

[26]The Department of Energy stated that 'A contribution of up to 70TWh/yr [28% of current electricity consumption] from those technologies which produce electricity directly, and up to 20Mtce from those producing heat [about 10% of current non-electrical primary energy consumption] may be possible by the year 2025' (Energy Paper No 55, HMSO, UK, 1988). The CEGB estimated an upper limit of 18% of renewble electricity by 2030, which gives a similar figure given the projected demand (submission to House of Lords Select Committee investigation on Alternativc Energy Sources, Report HL Paper 88-1, HMSO, UK, June 1988).

[27]Thomas Kuhn, *The Structure of Scientific Revolutions*, Chicago, USA, 1963.

[28]Andere *et al, op cit*, Ref 14.

[29]Sweden spends about 20% of its direct government energy R&D budget on the various renewable technologies; more is spent on nuclear fusion on any single renewable technology (*Source*: IEA, *Energy Policies and Programmes 1988*, IEA/OECD, Paris, 1989). Sweden is also lagging behind a number of other European countries in deploying wind energy.

[30]E. Jochem and E. Gruber, 'Obstacles to rational electricity use and measures to alleviate them', *Energy Policy*, Vol 19, No 4, May 1990, pp 340–250.

[31]'New farm and forest products – responding to the challenges and opportunities facing American agriculture', report to the Secretary of Agriculture, Washington DC, USA, 25 June 1987 (cited by R.H. Williams).

[32]D.O. Hall and F. Rosillo-Calle, 'Biomass, bioenergy and agriculture in Europe', 7th Canadian Bioenergy Research and Development Seminar, 24–26 April 1989, Canadian National Research Council, Ottawa, Canada.

[33]Climate Institute *et al*, *Report of the Forum on Renewable Energy and Climate Change*, various papers, Washington DC, USA, June 1989; also Sawyer, *op cit*, Ref 4.

[34]*Ibid*; also M. Browner, *Cool Energy – The Renewable Solution to Global Warming*, Union of Concerned Scientists, Cambridge, MA, USA, 1990.

[35]Sawyer, *op cit*, Ref 4.

[36]For example, a resume of studies by the International Energy Agency concluded that 'in the long term, we will have to rely on new technology, not yet forecastable' ('Impact of global warming', *Petroleum Economist*, March 1990, pp 83–84). A major study by the US Oak Ridge National laboratory concluded that 'Nonfossil energy sources individually and collectively are not yet ready to substitute massively for fossil fuels, and providing better technologies will require long lead times. Correcting this inadequacy will probably require an additional R&D investment of

about $1bn per year.' W. Fulkerson *et al*, *Energy Technology R&D: What Could Make a Difference?*, ORNL-6541/V1, Oak Ridge, TN, USA, May 1989.

[37]Despite the high funding of PV relative to other renewables, some key research work has still had difficulty getting funding. The initial stage of the research at Imperial College, London, which led to the theoretical advances reported in Part 1, Ref 47, was funded by Greenpeace; one of the researchers involved reported that colleagues in the USA had on occasion resorted to presenting their work as focusing on the closely allied problems of military infrared detectors in order to obtain funding or publication (private communication).

[38]As an indication, the aggregate annual revenue of the OECD oil companies alone averaged about US$600 billion annually over 1980–85; International Energy Agency, *Annual Oil Market Report*, IEA/OECD, Paris, 1986. Due to an oversight by this author, the diagrams showing relative R&D expenditures in Part 1 failed to indicate the total funding involved. Direct government expenditure by all IEA countries on all energy R&D in 1988 was US$6.8 billion, with the renewables combined accounting for 7.8%; the total over 1977–88 (Figure 1, p 526, was about US$120 billion, with the renewables (dominated by the Carter programme) accounting for 9.4% (all figures, 1988 US$)). Total UK government expenditure on energy R&D in 1985-86 (Figure 2) was estimated to be UK £565 (1985 currency), with renewables accounting for 2.3%.

[39]C.W. Hope, 'Assessing renewable energy research and development', *Energy*, Vol 7, No 4, April 1982, pp 319–333; M. Grubb, 'The potential for wind energy in Britain, *Energy Policy*, Vol 16, No 6, December 1988, pp 594–607.

[40]H. Bondi *et al*, 'Evaluation of the R&D programme in the field of non-nuclear energy 1985–1988,' European Commission, DGXII, Brussels; for discussion see *Financial Times Energy Economist*, Vol 89, No 6, March 1989.

[41]Sawyer, *op cit*, Ref 4, p 93.

[42]W. Nordhaus, 'The energy crisis and macroeconomic policy', *The Energy Journal*, Vol 1, No 1, 1980.

Postscript

The two articles which form the Cinderella Options (chapters 1 and 19 in this volume) were written in the first half of 1990. Reading them again in 1993, together with other papers in this volume shows how much has changed in certain respects, but also how little has changed in others. If rewritten today, the emphasis in some of the technical and political assessments might differ, but not greatly. On the technical side, I might for example pay more attention to small-scale solar thermal systems, and to the enduse interface in developing countries. Concerning the political side, renewable energy is rarely treated today with the derision often accorded to it in conventional energy circles even as short a time as three years ago, but it is still far from being a central part of the energy debate.

Assessments have become more numerous, more detailed and much more weighty: many governments are now conducting or extending updated regional and national studies which often point to a greater potential than previous perceptions and assessments. In some countries this has been accompanied by striking market developments, such as the UK's Non Fossil Fuel Obligation (Chapter 18), for example. Rapid expansion of renewable energy markets has occurred elsewhere in Europe too, most notably in Germany, whilst the US renewable energy industries have welcomed the Clinton administration as the end of the long blight of the 1980s. The physical contribution of modernized renewable energy technologies is still extremely small, but the 'paradigm shift' to which I refer in 'The Cinderella Options' seems to be gathering momentum, if anything faster than I had expected three years ago.

Chapter 20

Summary and Conclusions

Tim Jackson

The aim of this volume of collected papers (and of the series of articles on which it has been based) has been to address the following question: do renewable energy technologies offer the hope of providing clean, long-term energy options for the 21st century, or do they present only false promises with no significant hope of realisation in the foreseeable future?

Contributions to this book have covered technical, economic, environmental, institutional, political and social aspects of the renewable energy options. They have made assessment not only of the overall resource base, and the state of the art of technologies, but also of the costs and benefits of implementing these technologies, and the institutional factors which either impede or else might be used to encourage their implementation.

Almost without exception, and despite the fact that the papers have been written by a broad spectrum of industrialists, academics and policy analysts, the contributed articles have advocated a role for renewable energy which considerably exceeds both its current role in the world energy supply infrastructure, and most of the recent projections for its role in the near future. Almost unanimously, the authors have drawn attention to the environmental advantages of pursuing the renewable option. At the same time, there has been a general awareness of substantial obstacles to actual implementation within the existing infrastructure. A variety of suggestions have been made about overcoming these impediments.

Without a doubt the message purveyed by these contributions has been one of hope – both for the potential role of renewables in developing an economically and environmentally sustainable energy future, and for the potential flexibility and ingenuity of society in devising appropriate institutional structures within which that development can occur. Whether that hope will turn out to be fulfilled, is of course a matter for the future to reveal, rather than for me as editor to speculate upon. On the other hand, perhaps it is legitimate (indeed required of me) to make some kind of assessment of whether that message of hope is justifiable, on the basis of the evidence collected here. This is primarily the task I intend to undertake in this concluding chapter.

As I have already pointed out in the Editor's Introduction, there is a burgeoning global awareness of environmental issues, whose repercussions for energy policy are likely to be profound. In particular, the signing of the climate convention in Rio and the development of Agenda 21 studies will inevitably lead to an increased importance placed on the role of renewables. As this role develops, it is not inconceivable that it will foster an atmosphere of international technological innovation with high stakes for those who develop indigenous markets in renewable energy technologies at competitive prices. This in its turn would have a very positive impact on the development and implementation of renewable energy.

Whether I am right or wrong in these latter respects, the verdict of an impressive proportion of those who have contributed to this series has been positive. Those less than positive messages which have occasionally emerged have been in the form of warning lights, signalling the rocks on which renewable energy strategies might founder. For this reason they should be taken very seriously. Since it is my role as editor not only to present the consensus conclusions, but also to raise the flag and blow the whistle where necessary, I shall be careful not to overlook these warnings in what follows. Principally, however, I shall be concerned to convey the broadly undisputed conclusions which have emerged.

One almost unanimous call from the contributors to this series has been for the internalization of the environmental costs of energy supply. In Hohmeyer's contribution (Chapter 17), this call was made explicit through an incorporation of estimated environmental costs into the costs of electricity supply options. I shall consider this call rather carefully, since it is clear that many authors believe it to be critical to an appropriate and timely development of the technologies.

The motivation for the call for internalization of external costs stems from an acknowledgment of the

This chapter is based on T. Jackson "Renewable Energy – summary paper for the renewables series", Energy Policy vol 20(9) pp 861–883.

potential environmental advantages of renewable energy technologies. While I think it is important not to prejudge those advantages, I believe that in general the conclusion is correct. What I shall attempt to highlight, however, in the later stages of this summary, is the importance of developing an institutional or economic framework in which those advantages are appropriately recognized. In particular, I shall argue that an inappropriate framework could not only damage the development of a renewable energy strategy, but could also pose significant environmental threats in its own right.

Before developing these considerations, however, it would be remiss of me not to make some attempt to draw together the conclusions of the series on the question of the potential for implementation of the renewables, and attempt to summarize those factors identified as constraining that potential.

THE QUESTION OF POTENTIAL

An attempt to answer the question 'how much can renewables contribute to energy supply?' must distinguish between various different meanings to the question itself. This perhaps explains why different people have come up with such different answers when they have asked it. To make sense of such an enquiry, it is certainly necessary to be very clear about the kinds of assumptions one is making about the technical, economic and institutional conditions. There is no simple answer based on purely physical considerations, although this is a good starting point.

The first level at which the question may be asked concerns the extent of the physical resource base. How much energy, in physical terms, is flowing through the environment in a form amenable to capture or conversion? Next one must address the availability of capture and conversion technologies. Then one must address any other kinds of physical limitations that might be imposed on these conversion technologies. After this, it is necessary to ensure that the technologies proposed are not only feasible – in the sense of actually capturing the energy – but viable[T] in the sense that they capture more energy than is used to build and maintain the infrastructure around the technology itself. This question is related to, but not entirely the same as, the question of the economic potential: how much renewable energy can we afford to use? How much will it cost us? And then, even if these questions have all been answered, and even if renewables offer considerable prospects on this basis, the question of whether they will actually be able to make a significant contribution to energy supply is also dependent on various assumptions about the institutional infrastructure.

In the following subsections, I shall attempt to summarize some of the main conclusions from these various levels of questioning. At the end of the day some tentative conclusions can be drawn at the physical and technical level, some rather encouraging ones can be suggested even at the economic level. At the institutional level, much is dependent on political will, and appropriate infrastructural change, as we shall see later in the paper.

Table 1. Renewable energy resource base.

	TW
Solar radiation[a,b]	90,000
Wind[a,b]	300–1200
Wave[a,c]	1–10
Hydro[a,d]	10–30
Tidal[a,b]	3
Biomass[b]	30
Geothermal flow[a,b]	30

Sources: [a]B. Sørensen, 'Renewable energy, a technical overview', *Energy Policy*, Vol 19, No 4, May 1991, pp 386–391; [b]J. Twidell and T. Weir, *Renewable Energy Resources*, E. & F.N. Spon, London 1986; [c]Falnes and Løvseth (Chapter 5); [d]Sims (Chapter 6).

The resource base

The amount of energy arriving from the sun at the earth's surface – after reflection from the atmosphere, but before the various thermal and chemical cascades which convert high-quality[2] solar inputs into low-quality heat – is of the order of 100 000 TW. Since global commercial energy consumption is in the order of 10 TW, this 'solar inheritance' represents an energy flow four orders of magnitude greater than the flow of commercial primary energy resources through the human economy. The resource base for solar energies (including solar conversion technologies, wind, wave and hydro power, and biomass) is therefore enormous (Table 1).

Physical limiting factors

Unfortunately the question of potential is not so easily resolved as these promising estimates might suggest, for a number of reasons. The usefulness of energy sources in serving the needs of mankind is limited by two important physical factors. First, energy produces useful work in relation to its thermodynamic quality.[3] Low-quality energy sources cannot perform the same degree of work as higher-quality sources. This distinction is well known; for instance in power generation, a significant thermal gradient is required in order to drive a steam cycle turbine, and even then the efficiency with which that energy can be converted into mechanical work is limited by the Carnot efficiency. Low-grade heat is also useful to society, of course, and the benefits of using low-grade heat from power stations in combined heat and power plant are therefore considerable. Nevertheless, as the temperature gradient falls, the heat becomes less and less useful, until it reaches the ambient temperature conditions. The same degradation process occurs with both chemical and gravitational potential energies. The more degraded the energy, the less useful it is to us. In the case of hydro energy for example, the more useful sources are those with a significant gravitational potential energy, either as a result of high 'head' of water, or else in the case of low head hydro as a result of higher flow rates.

The second important factor limiting the usefulness of an energy source is its diffuseness. As Georgescu-Roegen describes it,[4] we receive the solar inheritance 'like a very fine rain . . . a microscopic mist'. The more diffuse the energy flow, the more difficult it is to utilize. It is not an accident of course, that the two major renewable energy sources used in the world today are biomass, and hydropower. Both of these sources of energy represent a considerable degree of concentration or accumulation of the diffuse solar energy income. In effect biomass and hydropower are the result of a trickle charge of diffuse solar energy in natural batteries or stores of thermodynamic potential. Fossil fuels, of course, are also believed to represent an accumulation of solar energy over very long periods of time. It is the degree of accumulation which has allowed these energy sources to become concentrated enough to provide useful sources of high-quality energy. Wind energy and wave energy are also to some extent concentrated energy sources, but to a far lesser extent even than high head hydropower. Solar radiation is virtually all flow, with no appreciable concentration or collection. For this reason, the vastness of the resource base of solar radiation is not, in itself, an indication of the appropriateness of solar energy as a useful energy source for society.

Technical potential – the recoverable resource

In general terms, the diffuse nature of the solar energy flows indicates the need either for some feasible collector device or else for some feasible energy storage techniques or both. In principle, of course, neither of these options is impossible. Indeed, each of the new renewable technologies of wind power, wave power, solar thermal collectors and photovoltaics (PVs) can be thought of essentially as much collectors of solar energy throughputs as they are converters of it. Biomass technologies by contrast are not so much collectors as converters of energy already collected and stored via photosynthesis. Tidal and hydro energy technologies are also converters rather than collectors, although in high head hydro schemes in particular collection is built into the technological infrastructure using dams and other civil works.

Table 2. Estimated recoverable resources.

	TW
Solar radiation[a,b]	1 000
Wind[a,b]	10
Wave[a,c]	0.5–1
Hydro[a,d]	1.5–2
Tidal[a,b]	0.1
Biomass	?

Sources: [a]Sørensen (op cit; [b]Kühne and Aulich (Chapter 3); [c]Falnes and Løvseth (Chapter 5); [d]Sims (Chapter 6).

As the papers in this book have illustrated, a wide variety of different kinds and techniques of collection and conversion have been developed. The actual potential for near- to medium-term development of renewable energy in individual countries is heavily dependent on the geographical context, the nature of ambient energy flows, demographic factors and the peculiarities of the energy supply infrastructure. On the basis of the known technologies, however, using estimated conversion and collection efficiencies, and the best knowledge about ambient energy flow rates, it is possible to convert the resource base (Table 1) into some broad, global, estimates of the recoverable resource. In Table 2, various estimates presented by different authors in this book are collected together.

It can be seen that estimated recoverable resources are considerably less than the resource base. Nevertheless, for many technology types these recoverable resources represent an available energy flow which is considerable when compared to commercial energy consumption. Particularly impressive is the estimated recoverable resource from solar radiation, which is still two orders of magnitude greater than the rate of global commercial energy consumption.

For biomass resources, Twidell and Weir[5] put the resource base at 30 TW. This is essentially that part of the solar energy input which is believed to contribute to the photosynthetic product. The question of a total recoverable biomass resource is more difficult to assess. Vitousek *et al*[6] estimate that human societies already appropriate 40% of the photosynthetic product. This indicates that we must regard estimates of global commercial energy consumption as representative only of a limited proportion of the total energy flows through the human economy. More importantly, when we come to consider the possibilities of appropriating an even bigger proportion of the photosynthetic potential through the conversion of biofuels, these considerations suggest some important limitations on sustainably recoverable resources.

The efficiency, power capture and rates of conversion of many of these technologies are certainly promising for renewable energy, but there are some other kinds of physical limitations, which must also be taken into account. One such limitation arises from the intermittent nature of many renewable energy sources. Grubb (Chapter 10) argues cogently that these limitations do not in themselves pose intractable problems for renewable energy. In particular, analysis has shown that intermittency only becomes a problem within existing electricity supply networks, once the contribution from renewables exceeds 30–40% of supply. Beyond this level storage will be necessary on some considerable scale.

A number of different storage options have been discussed throughout the book. Among these options, perhaps the most interesting for the long-term (because of its considerable potential) is the hydrogen option (Chapter 3 and Chapter 11). Hydrogen storage has attracted increasing attention for a number of years as a potentially benign energy storage option, with particular relevance to the transport sector where mobility and flexibility in provision of energy are of paramount importance. At the moment, as the analysis in Chapter 3 shows, the economics of the hydrogen economy distinctly unfavourable. There are, moreover, some safety issues surrounding storage and transport which need careful appraisal. Nevertheless, it seems clear that hydrogen presents a technological option not only for a clean storage medium, but also for a considerable improvement in the ability of renewables to satisfy the profile of energy demand across all sectors, including the demand for process heat, space heat, and transport.

The prospects for supplying heat from renewables are not confined to the development of hydrogen fuels, however, although the potential is more difficult to assess than that for the electricity sector. Passive solar demand could reduce heat demand quite considerably. Some authors have estimated 90–100% reductions in space heat demand in domestic and commercial building through a combination of energy efficiency measures and passive solar design. Solar thermal technologies are well suited to supplying process heat in conditions of strong insolation, but may be limited to space and water heating needs in temperate climates. Biofuels tend to offer greater flexibility than other renewables. Prospects here are limited in part by economic factors and in part by the environmental limitations on biofuels.

Thermodynamic constraints

Simplistic visions of renewable energy tend to suggest that it is a limitless free resource. The basis for this belief is that the energy being utilized flows through the environment regardless of whether or not it is converted for use by human systems. But this view is mistaken and potentially misleading for the following reasons.

The extraction – collection and conversion – of this energy will always rely on conversion technologies with limited efficiencies and specific material needs. It is inevitable that these material needs will in themselves pose limitations on the availability of energy. Certainly they will pose limitations on the cost of that energy. Just because the ambient energy flow is endless, it does not mean that it is a free source of energy![7]

Associated with the material requirements of conversion technologies is a requirement for energy to extract and process those materials, to transform them into the appropriate collectors, to maintain them and the institutional infrastructure on which they rely. The greater the diffuseness of the energy source, the greater the material requirements of the conversion process, and the greater the energy inputs required to build and maintain the energy conversion system. A technically feasible renewable energy conversion technology may exist which is capable of accessing significant useful quantities of energy for human use. A physically viable technology must return more energy to the user than has been invested in constructing the collection and conversion devices. This question of the energy return on investment of renewable energy technologies is absolutely vital to an assessment of the role of renewable energy. For this reason I regard the 'energy analysis' of renewables as one of the most crucial questions addressed by this series.

Energy analysis has had a particularly difficult history, partly because protagonists of the approach became involved with economists in what is probably best described as a lengthy process of mutual misunderstanding.[8] The vital role of energy analysis in assessing the viability of energy conversion technologies lies in allowing us to determine whether energy return on investment of a particular technol-

Table 3. Economic costs (costs in US¢/kWh (roughly current prices)).

Technology	1980	1990	2000[a]	2030[a]
Solar PVs[b,c,d,e,f]	100–400	30–100	10–15	4–6
Solar thermal electricity[b,c,e]	25–85	10–40	6–10	5.8
Wind				
onshore[b,c,d,f,g,h]	30–40	5–10	4–5	3–4
offshore[d,h]		8–20		
Wave[d,i]	40–80	10–20	8–10	5–8
Hydroelectric[d,g]	5–20	5–15	5–15	5–10
Tidal[d]	15–30	10–20	10–15	8–10
Biomass[b,c,d,g,j]	5–15	5–15	5	4
Transport[c,k]				
Conventional car	5–10	5–10	10–15	15–20
Hydrogen fuelled car from PV + electrolysis		100–500		

[a]Projected estimates; [b]Flavin and Lenssen Chapter 16, Table 1; [c]*Electric Power Research Institute (EPRI) Journal*, June 1991, p 17; [d]*Op cit*, Ref 29 and refs therein; [e]Kühne and Aulich (Chapter 3); [f]Hohmeyer (Chapter 17); [g]Gipe (Chapter 4); [h]Clarke (Ref 17); [i]Falnes and Løvseth (Chapter 5); [j]These are costs in ¢/kWh$_e$ for generated electricity and depend heavily on the price of feedstocks; costs for heat may be lower: Hall (Chapter 2), project costs of $1.80/GJ which is less than 2¢/kWH2; [k]costs in ¢/kilometre not ¢/kWh.

ogy renders it worthwhile developing. In particular, if it takes more energy to develop and maintain a renewable energy technology than that technology can deliver over its working life, then it is clear that the technology in question is not – in the long term – viable. It is at best a parasite on the existing energy supply system which cannot survive in the long term. At worst it could actually be detrimental in environmental terms, if it takes more fossil energy to operate that technology than would be required to supply the same final energy demand through conventional sources.

In certain cases, there may still be some environmental value in pursuing a technology without a positive return on the energy input investment, provided that the use of the renewable energy technology involved less fossil fuel consumption than was involved in supplying the same end-use using fossil fuels. This might be the case, for instance, for an electricity producing renewable which did not have a positive energy return on investment but which nevertheless used less fossil energy than required to provide the same need through conventional thermal fossil plant of limited conversion efficiency.

Happily, the various contributions to this book which have examined or reported on this question suggest that most of the renewables do indeed possess healthy positive energy returns on investment. In particular, Mortimer (Chapter 9) has presented an extensive survey of results suggesting that renewable energy technologies are not only beneficial in the weaker sense described above, but also viable in the stronger, long-term sense.[9]

Nevertheless, some caveats should be made about these results. As Mortimer has pointed out, much of the actual analysis was done several years ago now. In the intervening period, both the technologies themselves and the industrial base (on which statistical energy analyses are carried out) have changed. Some updating of these estimates is therefore essential to an accurate assessment of the renewable option. Particular attention needs to be paid, in this exercise, to ensuring that the energy analysis includes as many as possible of the many energy inputs associated with the construction, operation and maintenance not only of the technology itself but of the infrastructure required to support these processes. As Mortimer remarks, this assessment exercise raises difficult questions about system boundaries. The ultimate proof of the validity and long-term viability of solar technologies will probably have to be by demonstration. For this reason, the successful development of the 'solar breeder'[10] concept will mark an important point for renewable energy.

The concept of economic potential

Questions about the economics of renewable energy must of course pay careful attention to their material requirements. Since materials and energy are required in order to capture and convert solar energy, and these materials and energy have economic costs, there will always be an economic cost involved in utilizing this 'free' energy flow. In fact this cost may turn out to be prohibitive, particularly where the energy and material inputs are high. At this point the diffuseness of the renewable energy flows comes into play again. It is this diffuseness which

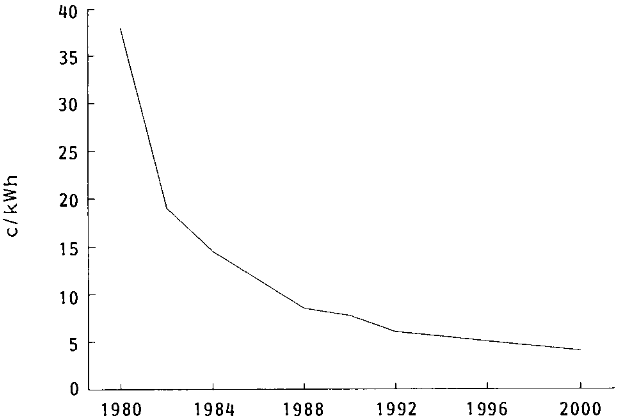

Figure 1. Costs of electricity from wind in the USA (1980–2000).

Source: Unpublished evidence from US Embassy in London, cited in *op cit*, Ref 29.
Note: Costs for 1980–90 are historical; costs for 1992 onwards are projected costs.

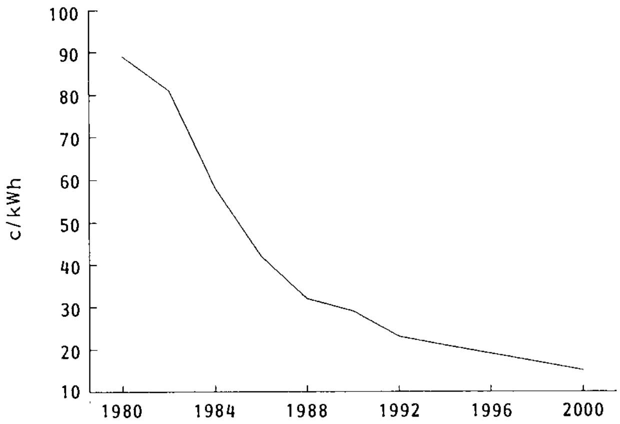

Figure 2. Costs of electricity from PVs in the USA (1980–2000).

Source: Unpublished evidence from US Embassy in London, cited in *op cit*, Ref 29.
Note: Costs for 1980–90 are historical; costs for 1992 onwards are projected costs.

results in the relatively high capital costs of many of the renewable technologies, these costs being in part a reflection of the high material and energy inputs required to access a wide area and achieve an acceptable power capture.

The concept of 'economic potential' is therefore an important element in the assessment of the viability of renewable energy. It reflects not only institutional aspects of the development of renewable energy technologies, but also genuinely physical inputs to the process of capture. Table 3 collects together those estimates of economic cost which have been presented by various authors (or collected by this author) during the course of preparing this series of papers.

Despite the remarks above, the existence of actual technology costs for renewables which are (in some cases)[11] higher than fossil fuel costs should not be taken to imply that economic factors will scupper the renewable enterprise. For a variety of reasons, we can reasonably expect the comparison between conventional energy technologies and renewable energy technologies increasingly to favour the renewables. In particular, economic comparisons presently fail to include the costs of depletion of resources, and the environmental costs of exploitation, and there are a variety of other subsidies which operate to favour fossil fuel consumption. In addition, the modern renewable energy technologies are, relatively speaking, infant technologies still in the process of technological evolution.

Costs in many technologies have fallen dramatically over the past decade. Flavin and Lenssen cite an order of magnitude reduction in the cost of PVs since 1980, for instance.[12] Many of the authors contributing to this book believe that some further substantial cost reductions are likely. Kühne and Aulich maintain that the 'cost reduction potential for solar components (eg collectors) is certainly higher than that of conventional components commonly used in establishing power plant technology'. They argue, however, against excessive optimism for further cost reductions in PVs, because the cost reductions achieved in the last decade have largely been on the module component, which represents only a proportion of the total cost.

Evidently, there will be some limit to the cost reductions associated with technological advance and increased production throughputs. On the other hand there has been a general consensus among the authors that we are still some way from that limit. Figures 1 and 2 illustrate actual cost reductions since 1980 and projected cost reductions to the turn of the century for wind technology and for PVs in the USA.[13]

How much?

The question of how much renewable energy can contribute to energy supply is shown from the preceding discussions to be far from simple to answer in a straightforward fashion, even before one starts to address the complexities of the social, political and institutional infrastructure. Attempts to provide a clear cut answer are probably foolhardy in the extreme. On the other hand it would be cowardly to have come so far and not hazard some intelligent guesses about the nature of the limitations on future development.

In summary therefore, we can say that the resource base is absolutely enormous, by comparison with the flow of conventional energy resources through the human economy. In addition, a knowledge of well-defined conversion efficiencies and the nature of the ambient conditions enables us to estimate recoverable resources which are once again very large compared with total global energy demand.

There are some kinds of physical constraints arising from the intermittent nature of some renewables. Taking Grubb's estimate of 30–40% penetration of the grid using intermittent sources, and assuming that electricity accounts for around 35% of the total energy demand in a typical industrial nation, suggests that an additional contribution to primary energy demand (on top of the contribution from existing renewables) of 10–15% could be comfortably met (technically) by intermittent electricity producing renewables. Additional contributions from non-intermittent electricity producing renewable technologies and from heat producing renewables could swell this considerably, even before the development of appropriate storage systems, leading perhaps to a comfortable 50% of current global primary energy demand met by renewable resources without any major technical developments or break throughs.

The ability to achieve this level of implementation will depend considerably on developments in the transport sector, since transport constitutes an ever increasing proportion of primary energy demand in industrialized nations. Several of the papers have discussed the use of renewable energy in transport. Generally speaking, the prospects for renewables in the transport sector are limited to three possibilities: first, the development of biofuels to substitute for or mix with conventional petroleum fuels; second, the development of an integrated hydrogen economy; or third, the development of enhanced battery storage and electric vehicles. The last two of these three rely on some considerable technological advance, if we are to assume more than a limited contribution from renewables in this sector.

Up to this 50% level of implementation, it would be fair to say that the major limitations will be economic, institutional and social rather than technical, or physical.

Beyond this level of potential contribution, we must expect that there will be a need for the development of an appropriate storage and distribution infrastructure. Hydrogen promises much in this respect, and provides the incentive for a vision of a wholly sustainable energy supply structure. This option should be regarded, however, with considerable caution. Its energy and material economics will be crucial to its long-term viability.

ENVIRONMENTAL IMPACT

The environmental impact of conventional energy sources has been one of the primary motivations for the development of renewable energy technologies, and in the absence of a favourable economic comparison, would remain one of only a few reasons for employing them.[14] On the other hand, no thermodynamic conversion process is likely to be without some environmental impact, simply because of the efficiency limitations imposed upon it by the laws of thermodynamics, and a closer examination of all the renewable energy technologies reveals that there are impacts, of one form or another, associated with each of them.

It is in fact difficult to find comprehensive objective analysis of the environmental impact of renewable technologies. In a set of five substantial volumes containing collected papers from the first world renewable energy congress[15] (ironically entitled *Energy and the Environment in the 1990s*) I found it difficult to find even a single reference to the environmental impacts of the technologies under discussion.[16] There seems to be an implicit assumption among advocates that renewable energy technologies are – if not actually benign – then at least by definition environmentally preferable to conventional energy supply technologies. There are certainly some sound physical reasons why this assumption might be valid. Indeed, in my opening article I pointed to the physical basis of renewable energy in utilizing ambient energy flows as being one reason to suppose that renewables are likely to be preferable to energy options which involve the consumption of fossil reserves.

There are also some compelling reasons why in practice protagonists of the renewables tend not to play up possible environmental impacts of their technologies. It is difficult enough for the voice of renewable energy to impact on the ears of an established fossil fuel energy infrastructure as it is, without admitting to the possibility of problematic environmental considerations. While this is an entirely understandable response, I do not believe that it is in the best long-term interests either of the environment, or even of the development of renewable technologies to neglect or underestimate the environment issue. There are several reasons for this point of view.

First, the principal colours of renewable energy are environmental. Without the supposed environmental advantages of the renewables, the case crumbles dramatically. For the long-term security of the environment it is therefore imperative that the case is water tight. Second, a failure to acknowledge environmental constraints at an early stage is likely to lead to a backlash from public opinion at later stages of implementation. Third, the physical nature of renewable energy technology in fact means that certain kinds of environmental impact are more likely than with fossil fuel technologies. Renewable energy flows, as already remarked, are diffuse. This diffuseness imposes inevitable material requirements on renewable energy technologies which are likely to be greater (in terms of the useful energy return) than those imposed on fossil fuel conversion technologies.

I have already referred to the danger of increased energy inputs associated with the diffuse nature of the source. But material inputs (and outputs) are equally important in environmental terms. Not only may certain conditions place material limitations on technology development, but also the extended use of certain kinds of materials may have significant environmental impacts. For instance, the use of solvents in the manufacture of PV cells, or the use of exotic materials to enhance performance of the cells, has potential environmental impacts which should not go unrecognized at an early stage. Indeed, policy decisions about the development of renewable energy desperately need to be informed by these kinds of considerations, as I shall try to demonstrate below.

Before doing so, however, it would be unfair not to acknowledge the attentions that have been paid to environmental issues in the book. Table 4 summarizes the main environmental impacts drawn attention to by various authors for the different technologies.

Table 4. Main environmental impacts of renewable energy technologies.

Solar	Land-use requirements, solvents use during cell manufacturer, toxic materials hazards during production and disposal (PVs)
Wind	Land-use requirements; visual impact; electromagnetic interference
Wave	Onshore: visual impacts, site disamenities; Offshore: conflicts with shipping
Hydroelectric	Large-scale: disruption of ecological and hydrological integrity of the region, community impacts, water pollution, induced seismicity
Tidal	Water quality and sedimentation pattern changes, ecosystems disruptions
Biomass	Land-use requirements, use of fertilizers, atmospheric emissions during conversion

Among the most interesting of the contributions on the question of environmental impact is Sims's discussion (Chapter 6) of the environmental impacts of large-scale hydroelectric power. The impacts of this technology relate mainly to ecological and hydrological disruptions, and the consequent damage to local ecosystems and local communities. Recent large-scale hydro developments tend to have suffered severely from environmental opposition, sometimes splitting the environmental lobby between those who are in favour of the dam because of its advantages over fossil fuel or nuclear generating capacity, and those who are opposed as a result of the impact on the local environment.

In favour of an environmental management approach to these problems, Sims cites the example of the construction of La Grand Rivière complex of hydroelectric stations in the St James Bay territory of Canada between 1975 and 1981, under the auspices of the Société d'Energie de la Baie James (SEBJ). Recognizing that the project had major sociological and environmental repercussions the SEBJ took a relatively far-sighted approach to the problem by: first, accepting the responsibility of the developer to carry out and pay for the necessary environmental studies; and, second, laying down certain principles for the development, namely that:

- all environmental legislation must be complied with;
- ecological considerations must receive the same attention as technical and economic ones; and,
- construction of the project must show that it is possible to develop important resources in harmony with nature.

As Sims notes, this 'seems to be an appropriate basis for the implementation of hydroelectric projects everywhere', and one might easily extend this recommendation to include all technological developments, and certainly all renewable energy developments. Even so, I suspect that large-scale hydroelectric projects will continue to find it increasingly difficult to gain public acceptability. Despite the good intentions of the SEBJ, for instance, there was some induced seismicity – relatively harmless as it turned out – at one of the La Grande complex reservoirs. And besides, as Sims acknowledges, measures for the protection of the environment may add significantly to the economic cost of the project.

Trade offs between economics and the environment are not unfamiliar to energy supply technologies, of course. For instance, the retrofitting of flue gas desulphurization reduces environmental burdens from acid emissions, but increases the cost of energy production. Many of the renewables also suffer from trade offs between environmental impacts and economic costs, albeit on a different scale.

In the case of wind energy, for example, in the search for improved economic performance, developers will inevitably look for high wind speed sites, which in relatively populated countries such as the UK are likely to be in areas of designated interest or natural beauty, where the (mainly visual) environmental impacts of wind energy are greater. This tendency increases local opposition to development of wind turbines, and increases lead times. Clarke[17] therefore suggests adherence to environmental siting rules, and the development of planning guidelines for local authorities.[18] But the economic trade off may still bite.

Similar trade offs are evident in other renewables. Productivity of biomass cultivation is enhanced, for instance, by the application of chemical fertilizers. But these add considerably to the environmental burdens of the technology. Efficiency of silicon solar cells is increased by the introduction of exotic materials such as gallium arsenide or copper indium selenide. But these substances impose increased worker risk, and potential environmental burden.[19] As Kühne and Aulich point out, there are difficulties in obtaining consent even for a manufacturing facility for doping PV cells.

I am not suggesting that these impacts are necessarily as severe, or even comparable with the global and regional impacts associated with fossil fuel combustion or nuclear power. Nevertheless it is important to know that these kinds of trade offs exist for the following reason.

In the absence of financial support for renewable energy, and given the institutional arena within which renewables must struggle to obtain a foothold, developers will tend to be driven by the need to reduce economic costs, by improving conversion efficiencies, or productivity yields, for instance by the use of exotic materials or chemical fertilizers. These kinds of developments will *increase* the environmental impact of renewable energy, whose main advantages over conventional systems was to have been *reduced* environmental impact. The failure of the instutional framework to allow renewables to develop under conditions favourable to the environment may therefore lead to the entrenchment of technologies which are increasingly hazardous to the environment.

This is particularly unfortunate, if it results from a failure to take adequate account of the environmental costs of fossil fuel energy. Almost without exception, contributors to the series have drawn attention to the external environmental costs of fossil fuel and nuclear technologies, and pointed to the advantages in recognizing this cost, either through an economic penalty applied to conventional fuels, or else to some specific institutional and economic incentive to the renewables. Hohmeyer's contribution (Chapter 17) re-presents and updates his now seminal work on the social costs of energy consumption.[20] This issue seems so important, and has been raised so consistently throughout the series that I reproduce some of Hohmeyer's assumptions and results here.

Among the costs which generally remain external to conventional pricing systems, but which are readily seen to be significant for the case of fossil fuels are the following:

- short- and long-term impacts on human health: physical injury, cancer, genetic damage;
- environmental damages to: flora and fauna, soils, water, buildings, the global climate;
- long-term costs of resource depletion;
- structural macroeconomic effects (unemployment for example);
- subsidies: R&D subsidies, investment subsidies, infrastructure and evacuation service costs in case of accidents;
- cost of strategic conflicts (eg Gulf War); and,
- psychosocial costs of serious illness or death.

Many of these factors already manifest real quantifiable economic costs to the nation. Other costs are currently unquantified, lying outside the realm of conventional markets. In some cases they are, moreover, extremely difficult to quantify. Nevertheless, it is possible to avoid actual quantification of externalities and use qualitative methods for preferring generation options with lower environmental impacts, such as the setting of specific technology targets, and the implementation of an economic ring-fence to achieve those targets. Alternatively, the imposition of environmental limits on particular pollutants forces the addition of 'control costs' to the conventional costs of generating.

There are nevertheless an increasing number of estimates of actual costs for specific damages.[21] Among them are Hohmeyer's calculations, based on relatively conservative calculations of the best quantifiable of the external costs. Figure 3 illustrates the

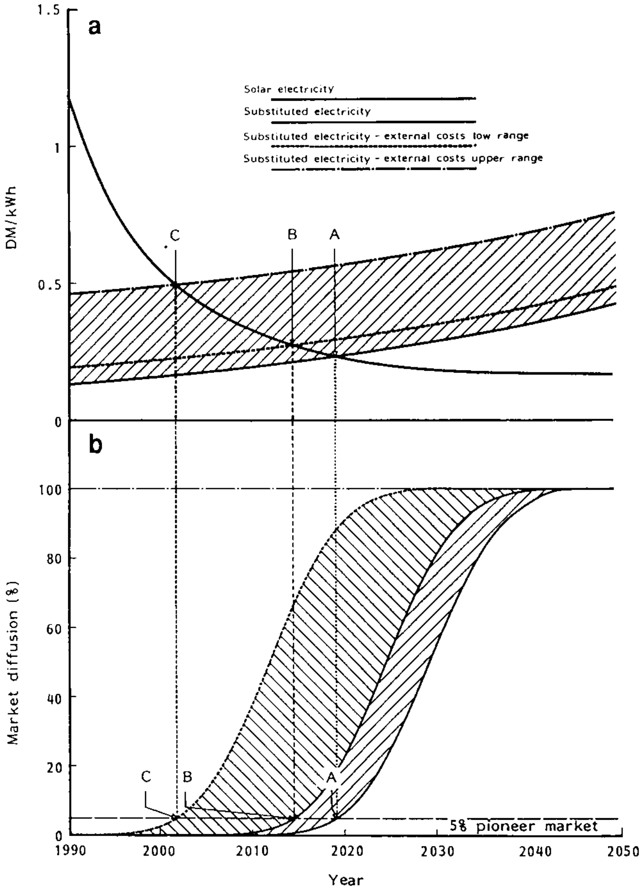

Figure 3. The effects of internalizing external costs on the market penetration of photovoltaics

result of incorporating environmental costs into the cost comparison between electricity from photovoltaics and electricity from conventional supplies.

Photovoltaics are assumed currently to generate electricity at a cost of just over 1 DM/kWh (approximately 60¢/kWh). Hohmeyer assumes that costs will fall along the black curve shown in Figure 3, crossing at some point the slowly rising costs from fossil fuel generation. The point at which they cross (and at which PVs become financially preferable to conventional generation) depends crucially on the degree of internationalization of external costs. When no external costs are included, Hohmeyer's results suggest that even by 2020, PVs will not have achieved any more than a 5% 'pioneer' market. With the fullest estimate of external costs included in the comparison, however, the results suggest up to 80 or 90% penetration of the market by the same period.

Although we must regard the actual penetration as somewhat illustrative – it depends on the exact nature of the penetration curve for the technology – these results are nevertheless striking. Internalization of external costs – or some mechanism for incorporating the existence of such costs into decisions about technologies – could have very considerable impacts on the prospective penetration rates of new technologies in the market.

It should be stressed here that Hohmeyer's results include external costs associated with PV production. Happily these costs seem to be rather small (despite the potential environmental impacts associated with PV cell manufacture and diffusion), and this conclusion is borne out elsewhere.[12] Nevertheless, the broad policy implications remain. Economic imperatives may drive renewables towards increasing environmental impact if policies are not devised which account for the environmental impacts of the conventional technologies.

In general terms the implications of internalizing external costs, or at least providing some kind of financial incentive to renewables on the basis of such costs is illustrated in Table 4. Here I have calculated a 'difference' cost for each renewable option, by using the economic costs for renewables collected in Table 3, and then subtracting conventional fuel costs (including external costs) from it. Although this result is not rigorous in any sense, because of the different sources for costs, and the different associated methodologies, the general picture illustrates how close to competitiveness many renewable technologies might be were environmental costs to be attached to conventional fuels.

Finally, it is worth remarking on a rather specific difference in the nature of the environmental impacts of many renewable energy technologies, compared with those of conventional technologies.

Table 5. Relative cost of electricity from renewables (with internalization of external costs) (costs in US ¢/kWh (roughly current prices)).[a]

Technology	1990	2000
Solar PVs	+5 to +90	−15 to +6
Solar thermal electricity	−15 to +30	−19 to +1
Wind		
Onshore	−20 to +1	−21 to −4
Offshore	−17 to +11	
Wave	−15 to +11	−17 to +1
Hydroelectric	−20 to +6	−20 to +6
Tidal	−15 to +11	−15 to +6
Biomass	−20 to +1	−20 to +1

Notes: [a] This table is compiled by taking the cost-estimates in Table 3, and subtracting a) conventional electricity generation costs of 6¢/kWh; and, b) a range of external costs 3–8 ¢/kWh, in line with the estimates in Chapter 17. The numbers in the ranges therefore correspond to the additional cost of the renewable option over the conventional option. When this cost is negative, the renewable option is cheaper than the conventional one.

Generally speaking there is a certain conceptual distance between the environmental impacts of conventional technologies and the lives of the general public. Impacts from fossil fuel generation, for instance, tend to be regional or global rather than local in nature, and although these impacts may affect local populations the link between cause and effect is not always made.

In addition, the conventional infrastructure of energy supply tends to remain largely invisible to the majority of the public. Local communities in the neighbourhood of power stations are clearly aware of their existence, but beyond the visual horizon, this impact is negligible. Quite simply, we do not always 'see' either the major polluters of our environment, or even the most damaging pollution. There is a tendency for 'out of sight' to remain 'out of mind', and objections against or actions for reduction in impact are likely to be limited to the local populations, rather than the public at large.

On the other hand the general public will tend to be more aware of the existence of renewable energy technologies when they are implemented. Since they operate best as dispersed, decentralized systems, and because of their need for a high capture area, they will inevitably be visible to a greater number of people.[23] This factor is exacerbated by novelty – electricity pylons are now an accepted feature of both urban and rural landscape, but the erection of wind turbines still arouses strenuous objections. What we are faced with here is a dilemma. In terms of potentially catastrophic, global environmental impact, the conventional energy supply technologies offer considerably greater hazards (and costs) than the renewable technologies. But the renewables are more *present*. They offer us the spectre of our technological lifestyle in a generally highly visible form.

Dealing with this dilemma is a social and political problem. It is not about costing environmental impacts, nor about relative technical merits. It is about the readiness of society to face and to accept the impact which its own technological demands make upon the environment. Enthusiastic technological advocacy is not likely (fortunately or unfortunately) to influence this. To my mind, the better course of action is to open out the debate by acknowledging those impacts which do exist, and facing society with the choices which must be made.

POLICY CONSIDERATIONS

Renewables offer considerable potential for displacing conventional energy sources, and in some cases are already competitive with conventional sources. They offer particular environmental advantages in terms of reduced atmospheric emissions. Nevertheless, they are not yet widely adopted, beyond the conventional large-scale hydro resources which have been developed over the last few decades. What is the explanation for this? Can it all be put down to the unfavourability of the economic comparison? Are there other institutional factors involved? How can these factors be overcome, and what measures need to be taken to ensure that the true economic potential for environmentally sound energy supply can be implemented?

These questions were among the most important to be addressed in this series of papers, and they have been tackled by the various authors in a variety of ways. Some differing points of view have been expressed, some interesting individual assessments have been made, but largely there has been a strong consensus about the overall factors which are contributing to the failure of renewables to impact on energy supply to any significant extent, and also about the kinds of policy measures which will need to be put in place in order to rectify this.

An initial point to make is that there is still, of course, an economic penalty for at least some of the renewable technologies, when compared with conventional fossil fuel supply. From the perspective of an uncritical economic analysis, one might therefore be tempted to suggest that the renewables have made no mark because they are simply too expensive. As and when the technology costs fall, then renewables will begin to take their place in the energy supply infrastructure according to the principles of a competitive market. While there may be some truth to the suggestion that when costs fall low enough renewables will begin to impact on the market, two things lead us to question the completeness and accuracy of this position.

First, some at least of the renewables are competitive or very nearly competitive with fossil fuels. Why are these technologies still struggling for a substantial foothold in the market? Second, the case of nuclear fuel indicates that with sufficient government and industrial will, some very expensive technologies are capable of making substantial impacts on the market, on a basis which is not economically competitive. Nuclear generation has been the beneficiary of considerable subsidization (often concealed) and considerable vested interest (both commercial and military) since the early days of its development. Given the potential environmental advantages of the renewables, why has this not happened for them?

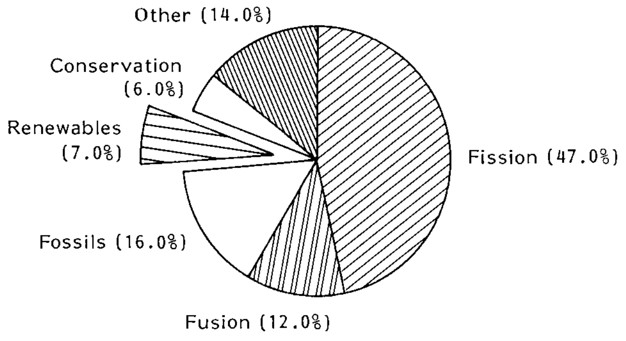

Figure 4. Energy R&D spending by IEA governments (1989).
Source: OECD 1990 cited in Flavin & Lenssen, Chapter 16.

In fairness, it should be remarked in response to this second point, that the nuclear case was made for a long time on the basis that it *would* be economically competitive, and that once the unforeseen costs of the technology began to escalate, the development of nuclear power has been virtually halted. Nevertheless, as many of the contributors have pointed out, the level of research and development funding has continued to favour nuclear power over the renewables (Figure 4), and this is a situation totally at odds both with the potential environmental advantages of the renewables over nuclear power, and with the complex technological needs still to be addressed within the many different areas of renewable energy technology.

Among those needs, Grubb (Chapter 19) has identified the following three broad areas:

- resource surveys; wind regimes; insolation rates, soil characteristics and so on;
- fundamental research: basic areas of PV technology, power electronics for interfacing and control, biomass conversion chemistry etc; and,
- technology development.

In the same paper, Grubb answers the problem of the slow impact of renewables by suggesting a broad underlying scepticism towards and ignorance about renewable energy. He points in particular to:

- a primary lack of data about renewable resources and technologies, leading to an underestimate of their potential;
- excessive conservatism in technology and resource assessments;
- failures in transferring knowledge to the policy community; and,
- failures of vision in applying existing and broadly accepted assessments into energy projections and policies.

These issues are clearly important, particularly at the level of attitudinal responses and institutional biases, and they may explain, for instance, why R&D spending has remained so low. Similar concerns about the nature of institutions have been voiced by other contributors to the series. Twidell and Brice[24] have highlighted the lack of basic information. Flavin and Lenssen (Chapter 16) point out the power of various institutional lobbies in maintaining fossil fuel and nuclear contributions to energy supply, and call for a reform of the international energy institutions. Several authors have suggested the development of national, and possibly international, renewable energy development agencies.

Twidell and Brice point out the advantages of developing renewables through decentralized exploitation of what they call 'niche opportunities', local or regional hotspots of ambient energy flow, which match appropriate demands. The advantages of such an approach are potentially improved cost-effectiveness, a decentralized, and modular development well suited to the nature of renewable energy technology, and a technological learning curve, somewhat cushioned by favourable circumstance. Disadvantages might include a somewhat slow development, and a potential marginalization of the technologies. Others in the series have argued that it is time for renewables to begin to displace the power of the conventional fuel supply lobbies.

These are all important insights into the development of an institutional context more sympathetic to the emergence of innovative renewable energy technologies. What these suggestions tend to bypass, however, is the acknowledgment of certain hard, institutional and economic blocks which stand in the way of renewables investment and deployment. In the next section of the paper, I would like both to illustrate some of these economic manifestations of institutional intransigence and to identify appropriate policy initiatives for tackling them.

INSTITUTIONS AND ECONOMICS

The existing energy supply structures in the industrialized world is the result of almost two centuries of technological development on the basis of fossil fuels (and more recently nuclear power). That these technologies should have established themselves in rather specific institutional ways is therefore not surprising. But much of this historical structure imposes powerful economic implications on the ability of renewables to enter the existing market.

For example, over the last 40 years or so, electricity supply structures in developed and industrializing countries have been built up largely as a result of the access of utilities to cheap, often state-subsidized, capital. This has resulted in two important institutional features of the existing electricity supply market.

In the first place in some at least of those countries, there is now a considerable danger of substantial overcapacity in supply. In the UK this overcapacity is striking. Scotland currently possesses a 218% overcapacity of supply. In England and Wales, in the wake of the privatization of industry, proposals exist for a total of 30 GW of new (gas fired) electricity generation plant, far more than is conceivably necessary to meet technical shortfalls. In France, a massive state-funded nuclear construction programme has led to a similar overcapacity in supply.

Quite apart from anything else, this overcapacity problem operates as a significant disincentive to investments in energy efficiency, particularly if it is reinforced by a price regulatory structure which impedes cost recovery of the energy efficiency investments and passes through the fuel costs.[25] Equally, however, it means that economic comparisons on the basis of equitable assessments of the costs of renewable technologies with conventional technologies are virtually meaningless. Very low marginal costs for electricity are the inevitable economic result of overcapacity. Renewable energy investments must compete not with the costs for conventional energy annuitized at a common social discount rate but rather against the short-run marginal costs of (often subsidized) existing plant.

In the UK, this situation means essentially that there will be no real competition between renewable technologies and conventional plant for at least 15 or 20 years, except within a financial ring-fence established by government. Although this is in fact the policy currently proposed by the UK government for development of renewable energy, it is clearly far from ideal to subsidize a competitive technology, on the basis of historical distortions in the institutional structure. This strategy is also subject to the problem that a ring-fence is likely to marginalize the ring-fenced technology in the context of the real market, and limit its application to pre-established government targets. In reality this may well mean considerably less renewable energy than would soon be economically competitive.

The second implication of the historical development of energy institutions is the emergence of strong, often monopolistic institutions supported by favourable regulatory structures and with continued access to contracting arrangements and sources of capital which are inherently cheaper than those available to new, independent investors. The technological and historical inertia associated with these semimonopolistic institutions means that they are not likely to invest in innovative technologies. On the other hand, prospective new investors find the real economic framework weighted heavily against them, as the following analysis shows.

The economic comparison between different electricity supply technologies (assumed to be supplying the same system in more or less the same manner)[26] is generally made on the basis of the so-called generation cost methodology which calculates a cost per kWh on the basis of capital costs (annuitized over the lifetime of the project), fuel costs, and operation and maintenance costs. Generally, a common discount rate is chosen to annuitize the capital costs, thus providing a supposedly equitable basis for the comparison. Many of the costs for renewable energy technologies quoted above are on this basis.

In practice, however, two specific kinds of inequities can creep into this economic comparison. In the first place, the cost for the technology is not a well-defined concept in the electricity supply market place. A concept which is better defined is the 'buyback price' required by the investor in order to achieve a certain internal rate of return over a certain 'investment period'. Both the required rate of return and the investment period are highly influential in determining the required buyback price if the investment is to be considered worthwhile. Generally speaking, and other things being equal, the shorter the investment period and the higher the required rate of return, the higher the buyback price required for electricity supplied if the investment is to be viable to the investor. The problem for renewable energy is that both the required rate of return and the investment period are heavily dependent on a number of institutional factors, some of which may be beyond the control of the investor.

To illustrate this, let us consider two separate investors considering wind energy investments in sites with the same average wind speed conditions. In both investments (Project A and Project B, let us say) the technology being considered is a wind turbine with a predicted annual load factor (given the turbine rating and site conditions) of 30%, installed capital costs of £1000 per kW, and operation, maintenance and site costs estimated at 3% of the total capital cost per year.[27] Investor A is an electricity supply utility, let us suppose, while investor B is an independent producer, hoping to corner a place in the developing market for wind energy. For the purposes of this comparison we shall ignore any availability of subsidies and assume that other conditions (rates, site costs, overheads and so on) are all equal and accounted for within the O&M costs.

Now the utility investor is likely to operate under a required real rate of return of 8%, let us say, and because of his historical place in the market, his financial status, and the security of his contract for sale of electricity to the local purchasing agency or distribution company is able to use an investment period corresponding to the lifetime of the technology (which we suppose in this instance to be 25 years). These conditions mean that his required buyback price for the electricity from the investment is 4.7p/kWh.

The independent producer, on the other hand, is constrained by the cost of commercial capital (interest rate) to use a higher rate of return (part of this higher cost being due to the innovative nature of the investment, and the risk perceptions of the capital market) of 11%, let us say. Additionally, he is guaranteed purchase of his electricity at a price to be agreed only over a contract period of six years, which is therefore the period he must adopt as his investment period. To this investor the buyback price he must attempt to negotiate with the distribution company or purchasing agency rises to over 10p/kWh, more than double the buyback price required by the utility investor.

Here then is a very clear example of the way in which institutional arrangements affect the perceived costs, and hence the financial viability of investments in renewable energy projects. While this may seem to be an extreme comparison, it closely resembles the economic conditions within the UK at the moment.

Under the privatization of the UK ESI (Chapter 18), the government introduced an obligation on the distribution companies to supply a certain percentage of their electricity from non-fossil sources. This is the ring-fence referred to earlier. Originally intended to support the nuclear industry in the interests of diversity, this non-fossil fuel order (NFFO) was developed to include a special tranche for the renewables. Under the conditions of the order the extra costs involved in supplying this renewable energy were obtainable via a fossil fuel levy imposed on conventional fossil fuel generation. The order is fulfilled under a reviewing system in which applications below a certain cut-off point within each individual technology band are each allocated consent on the basis of the highest required buyback price within that band. For wind energy the band price in the recent quota was around 11p/kWh. Potential investors were subject to commercial costs of capital, and the threat of a 1998 cut-off for the NFFO meant that they needed to recoup that capital within about six years – exactly the conditions supposed for investor B above.

The overall effect of these kinds of real economic factors in an open market situation would be to render wind energy an exceedingly unprofitable investment requiring very high rates of return for private investors, thus discouraging all but the most dedicated afficionados of wind energy. In practice, the rather idiosyncratic mechanism of the UK government's NFFO has allowed a small tranche of wind energy to move towards development, but under financial conditions which do not reflect the true costs of wind energy at all, giving the impression that extremely high buyback prices are needed if wind energy is to be a viable proposition.[28] This in itself may lead to only limited expansion of the targets for implementation of renewables in the future. The ring-fence fences renewables in as well as fencing conventional capacity out!

The last few years have witnessed an increasing interest in private investment in wind energy, from a number of directions: wind energy technology manufacturers, private cooperatives including farmers and local communities, and entrepreneurs interested in cornering a part of the emerging private generation market. Surely these different interests should be encouraged, offering as they do a spontaneous and potentially beneficial effort towards the development of renewable energy technology? And yet non-utility investors are financially discouraged from investing in wind power projects within existing institutional frameworks. The utilities meanwhile, through a mixture of historical factors, technological inertia, and institutional anomalies have generally been slower in developing such investments.

What can feasibly be done to ease this situation in an efficient and cost-effective fashion?

In the UK, as I have mentioned, the case for wind energy (and a number of other renewable energy projects) is being eased perversely by the idiosyncratic mechanism of the NFFO. There is certainly a case for a smoother, perhaps less idiosyncratic approach based on the same idea, namely a hypothecation of fossil fuel levies to ease the financial burdens of new, environmentally preferable sources of generation.

In Denmark and California the private market for wind energy has been encouraged by tax credits and subsidies, and these methods too have had some discernible success. The dangers of these kinds of incentives are, however, twofold. First, oversubsidization leads to a degree of technological complacency and the implementation of technologically substandard and economically suboptimal projects. Second, and perhaps more devastatingly in the long run, changes in subsidy levels have tended to be abrupt, and therefore disruptive in ways that seem out of proportion to the actual degree of the change. A prime example of this is provided by the collapse of Luz International early in 1992. Their bankruptcy forced the abandonment of several projected solar parabolic projects and jeopardized the continued operation of existing plant. Luz blamed not only the loss of certain state tax credits but also the uncertainties surrounding the renewal of both state and federal credits, leading to loss of confidence both within the company and among potential investors.

Of course, some kind of mechanism for an internalization of environmental costs will also aid the financial cause of the renewable technologies, and may provide an added incentive, particularly for utility investment in renewables, if the mechanism employed is appropriately designed. The discussion of the internalization of external costs in the preceding sections focused on a quantitative costing of environmental damages, and the incorporation of these damages into fossil fuel prices (for instance). There are many difficulties with carrying out this exercise, but that does not necessarily mean it should not be attempted. As Stephen Salter has pointed out 'we often assume that if some cost is difficult or embarrassing to calculate the answer is zero. We then optimize the system at the expense of the feature we are neglecting'[29] – in this case the environment. In fact, with regard to the environmental costs of fossil fuelled energy, there is only one thing we can be certain of: that zero is the wrong number!

Costing environmental damage is not the only way of internalizing known environmental costs, however. Hypothecation of fossil fuel levies, in the fashion described above for the case of the UK, on the basis of a declared target for implementation of renewable is certainly one alternative – subject to the caveats already made. Other alternatives include simple financial 'adders' applied to fossil fuel prices, the application of strict environmental emission standards for polluting emissions, the manipulation of allowed rates of return to utilities on the basis of environmental performance, and the setting of required targets for renewable energy with costs retrievable from consumers.[30]

One of the most interesting proposals for facilitating the cost-effective implementation of renewable energy revolves around an appropriate institutional framework for dealing with risk. In the example cited above, investor B was subject to a higher cost of capital (interest rate), which meant that his own required rate of return for the project was significantly higher than the likely rate of return for the utility. A part of this difference in required rate of return would have been a result of the risk perceptions of the commercial capital market. 'Wind is a new technology, and innovation is risky.' That is the way in which the project would probably be perceived by investors. In order to account for this supposed increase in risk, a certain added factor would be made to the rate of return applied to the capital.

Awerbuch[31] presents a number of reasons why this discount rate adjustment may be overestimated for certain kinds of renewable energy investment. These reasons include the advantages of such investments in terms of modularity, low marginal costs, and overhead reductions. The most striking element in this analysis, however, is the comparison between the risk assessment made on such a project, and the risk assessment conventionally made on fossil fuel investments. Risk, in the context of fossil fuel investments, is dominated by the risk associated with fossil fuel price changes. But this risk may not affect the rate of return of the project if the institutional structure allows for fuel cost increases to be passed through to the consumer.[32]

Additionally, we might have considered the risk associated with future environmental damages from fossil fuel combustion. But again, in the absence of an appropriate institutional structure, this risk is not borne by the investor, but by society at large.

At this point the implications of the failure of utilities to invest in new renewable technologies becomes much clearer. Not only is the investment infrastructure skewed towards the conventional technologies in terms of the discount rate and (possibly) the investment period. But this inequitable situation is reinforced by the structure of price regulations, which treat different investments in unjustifiably different fashions. We also begin to see, from the perspective sketched out here, how the need for investment in strategic resource defence (the Gulf War, for example) which I have alluded to in my introductory chapter is being reinforced by the same inequitable structure.

In the bluntest possible terms, the failure of existing infrastructure to adequately incorporate different risk elements on an equitable basis is tantamount to a provocation to armed conflict. Or, put another way, it is an incentive to environmental destruction.

These are powerful conclusions, and of course must be treated contextually. In some contexts, these kinds of inequities exist, and are reinforced by these kinds of regulatory structures. In other contexts, attempts are increasingly being made both to incorporate some financial incentives for the development of renewable technologies, on the basis of their environmental advantages, and to develop equitable regulatory and financial structures, under which these investments can be effectively carried out. The analysis in this section serves to illustrate some specific senses in which the institutional infrastructure can operate against the best interests of renewable energy, against the best interests of the economy, against the best interests of the environment, and against the best interests of global security. There is no better indication that it may be time to address these structural elements and find ways to change them.

RENEWABLES IN DEVELOPING COUNTRIES

Several papers in this series have addressed the development and deployment of renewable energy in developing countries. Hall *et al* (Chapter 12) looked at some specific biomass case studies, and highlighted the over-riding importance of local conditions in determining the success of the projects, and the need to develop such projects with full local involvement. Foley (Chapter 15) broadened this perspective by examining the past successes and failures of renewable energy development assistance in developing countries. The lessons from this study were harsh and uncompromising.

Some legitimate and competitive niche opportunities do exist for specific renewable technologies in developing countries. But the record of renewables energy projects set up using development assistance in developing countries has been poor. Schemes have been dogged by technical failures, high capital costs, falling oil prices, inadequate technical and economic assessments, and in some cases, simply inappropriate technological choice, and this all in spite of the setting up of various international development assistance agencies with apparently good intentions.

Foley argues for increased vigiliance and rigorous assessment. Hall (Chapter 12) and Rady (Chapter 13) both call for the close involvement of local communities. All of the authors warn against viewing developing countries as some kind of seedbed for renewable energy. In many cases, technologies have either not been technically developed enough for installation, or else were unsuited to the relatively underdeveloped technological support structure in the locality. In some other cases, projects have jeopardized the successful development of a sustainable local energy supply strategy.

Once again, there is a lesson here for Western policy makers. In search of niche markets and economic opportunities, manufacturers are likely to be driven into seeking development assistance opportunities in foreign markets if the appropriate financial and institutional conditions do not exist in home markets. Whereas this kind of international development is not problematic if it occurs between countries at equal stages of technical and economic development, and with equally rigorous assessment procedures, there is a need for vigilance to prevent renewable energy being sold to the developing world (even via assistance agencies) as a substitute for appropriate technological development in the West.

Finally, I cannot leave this subject without drawing attention to Palmer's cautionary tale (Chapter 14) of the development of the country boats in Bangladesh. In some sense, this returns me to the remarks I made in one of the opening sections concerning the industrial revolution. The virtue of fossil fuels was to bring to industrializing nations very necessary, highly flexible, mobile energy carriers, with which to modernize industry, construct new societies, and improve standards of living. Whatever the virtues and vices of that particular process in retrospect and however one may feel about some of the more far-reaching consequences, we cannot expect that those nations still to traverse their own development paths, will forgo technical advances which could improve their living conditions, simply for the sake of out-of-date concepts or imported ideals.

The use of renewable energy in developing countries can only be expected to displace the use of fossil fuels, if genuine economic and environmental advantages are offered by it. This in itself suggests that, as Kristoferson[33] notes:

> The cutting edge of renewable energy technology development will have to be in the industrial countries, particularly in the IEA countries. If nothing happens there, nothing will happen at all.

CONCLUSIONS

The prospects for renewable energy are good. The resource base is enormous. There are a number of well-developed technologies, whose conversion efficiencies (improving all the time) ensure a very considerable recoverable resource. The economic costs of many of these technologies are fast moving into a competitive position with fossil fuels, and in addition there is an emerging shift in political attitudes, in part because of a burgeoning environmental awareness, and the development of international agreements on actions on climate change, and in part because of slowly growing awareness of the economic, social and humanitarian costs of the strategic security needs associated with import-driven, fossil-fuel dependency. All of these factors imply a promising future for renewable energy.

At the same time a number of institutional obstacles stand in the way of genuine progress towards implementation. Some of these obstacles have specific economic implications, ensuring that even those renewable energy technologies which are competitive under common assumptions are unable to compete equitably against conventional fuel sources in the existing infrastructure. While these institutional/ economic obstacles exist, developers of renewable energy will be forced to seek cost reductions and efficiency improvements even if this can only be done at the cost of increased environmental impact. The maintenance of inappropriate economics and institutions may therefore not only significantly reduce the potential for implementation of renewable energy, but may in addition jeopardize the environmental integrity of the whole endeavour.

A variety of different policy initiatives are available for governments who are open to aiding the development of renewable energy technologies. These include the establishment of strict emission limits on conventional fuels, the taxing of emissions, the setting of targets for implementation of renewables, and the development of subsidy schemes, tax credits systems, or price ring-fence systems for renewable technologies. Two particular policy aspects have been highlighted in this summary paper. On the one hand recognition has been given to the need for development of instruments appropriate to the internalization of the external costs of energy consumption – either through quantitative costing procedures or through qualitative mechanisms for preferment. On the other hand attention has been drawn to the need for development of impartial, and even-handed regulatory structures. These structures must be capable of ensuring equitable financial conditions to all energy supply technologies, in particular by dealing appropriately with short- and long-term societal risk.

To do justice to the breadth and depth of the contributions to this book, would be a mammoth, probably impossible, task. In this paper, I have sought to convey the main conclusions, and the broad consensus of opinion amassed in the preceding papers, while at the same time recognizing the reservations expressed. To summarize that consensus, it would suffice to answer the question which this book set out to address, in the following way. Provided that the appropriate institutional steps are taken, provided that there is sufficient political will and institutional flexibility, renewable energy offers considerable hope for a sustainable, affordable and are equitable energy future for mankind.

[1] I am using here a linguistic distinction introduced by N. Georgescu-Roegen, 'Energy analysis and economic valuation', *Southern Economic Journal*, Vol 45, 1979, pp 1023–1058.

[2] The distinction between high- and low-quality energy sources is a thermodynamic one, quality being a measure – broadly speaking – of the ability of a particular energy source to carry out work. While the energy from the sun covers a broad spectrum from ultraviolet to infrared, the energy reradiated from the earth has been degraded to low level heat in the infrared range.

[3] More correctly, in relation to its thermodynamic potential gradient, but since the ambient conditions are more or less constant, this requires energy resources of significantly higher quality than the ambient conditions in order to perform useful work.

[4] N. Georgescu-Roegen, 'Energy and economic myths', *Southern Economic Journal*, Vol 41, No 3, 1975, pp 347–381.

[5] Figure 3, Chapter 2.

[6] P. Vitousek, P. Ehrlich, A. Ehrlich and P. Matson, 'Human appropriation of the products of photosynthesis', *Bioscience*, Vol 36, 1986, pp 368–374.

[7] In September 1991, a particular experimental result achieved in fusion energy at the Culham laboratory in the UK, was hailed as a breakthrough for cheap and essentially limitless supplies of energy for the world. The basis for this claim was that – at a stage of technological development considerably beyond the existing one – it may in the future be possible to fuse deuterium molecules; since deuterium is abundant in sea water, and sea water is abundant on earth, this was supposed to represent limitless free energy for mankind. Arguing that fusion is a limitless source of energy is like arguing that fossil fuel combustion is limitless, just because of the abundance of oxygen in the atmosphere. The correct way to assess the potential for any energy conversion technology – and this must be taken to include the renewable energies – must be to look not at the abundant throughputs but at the limiting material and physical constraints.

[8] Contributed to in the course of this series by David Pearce's heated response (*Energy Policy*, Vol 19, No 9, November 1991, p 813) to Nigel Mortimer's work (Chapter 9).

[9] Confirmations of this have been provided by some other authors. For instance, Winter reports some results (Chapter 11, Figure 3) which concur broadly with those collected in Mortimer's paper. It should be noted that there are three different concepts which essentially report the same result, namely the energy return on investment (EROI), the net energy requirement (NER) and the energy ratio or energy gain factor (EGF). These concepts are

related to each other by: NER = 1/EGF = 1−EROI.

[10]That is a technological subsystem in which solar converters and their associated infrastructures are built and maintained using only solar energy.

[11]With some notable exceptions.

[12]Table 1, Chapter 16.

[13]See also Figure 9 in Chapter 3; Figure 2 in Chapter 5; and Table 1 in Chapter 16.

[14]Other reasons concern questions of long- or short-term resource scarcity.

[15]A. Sayigh, ed, *Energy and the Environment in the 1990s: Proceedings of the 1st World Renewable Energy Congress*, Reading, UK, September 1990, Vols 1–5, Pergamon Press, Oxford.

[16]Similar observations might be made, of course, of many new technologies, and this represents a general problem in technology innovation. In the case of renewable energy, however, the omission is all the more important because of the supposed environmental benefits of renewable energy.

[17]A. Clarke, 'Wind energy: progress and potential', *Energy Policy*, Vol 19, No 8, October 1991, pp 742–755.

[18]Such guidelines already exist in Denmark for instance.

[19]Interestingly, however, one of the most promising advances in PV technology involves the development of thin film amorphous silicon cells, which promise both significant cost reductions on conventional cells and also reduced environmental burdens.

[20]O. Hohmeyer, *Social Costs of Energy Consumption*, Springer-Verlag, Berlin, 1988.

[21]A summary of some of these estimates is to be found in J. Twidell and R. Brice, 'Strategies for implementing renewable energy: lessons from Europe', *Energy Policy*, Vol 20, No 5, May 1992, pp 464–479.

[22]A Baumann and R. Hill, *External Costs/Benefits of Energy Technologies – Development of a Methodology*, Final Report, JOUR-0020-UK(CH), Newcastle Polytechnic, UK, Table 2.

[23]This increased visibility does not necessarily correspond, as some have suggested, to a vastly increased requirement for land. Gipe, for example, presented some valuable figures on the land-use requirements of different energy technologies, illustrating that many solar and wind energy plants, actually use less land per MW generated than conventional coal fired stations.

[24]*Op cit*, Ref 21.

[25]T. Jackson, *Efficiency without Tears: No-regrets Energy Policy to Combat Climate Change*, Friends of the Earth, London, UK, 1992.

[26]As baseload, for example.

[27]These costs are somewhat conservative in comparison with some of the estimates quoted already in this paper.

[28]The financial conditions under which these investments laboured are in fact equivalent to the imposition of a rate of return of almost 25% under an equitable generation cost methodology.

[29]House of Commons Energy Committee, *Renewable Energy*, Fourth Report, Session 1991–92, March 1992, HMSO, London, UK.

[30]For a comprehensive account of the use of some of these measures in practice, see T. Woolf, *Accounting for the Environmental Externalities of Electricity Production – A Summary of US Practice*, Association for the Conservation of Energy, London, UK, 1992.

[31]S. Awerbuch, 'Measuring the costs and benefits of new technology: a framework for photovoltaics', in *Proceedings of the Solar World Congress*, Denver, 1991, International Solar Energy Society, Pergamon Press.

[32]This passthrough of costs is in some cases a direct result of price regulation structures. In other cases it is a more complex interaction between contract arrangements, and the historical effects of horizontal and vertical integration within the market.

[33]L. Kristoferson, 'The sleeping renewable beauty – will the prince ever come?', presentation to the IEA Conference on Technology Responses to Global Environmental Changes, Kyoto, Japan, November, 1991.