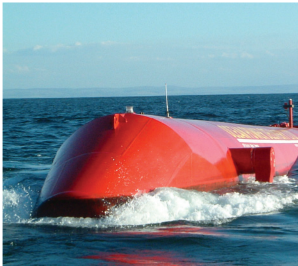
ENERGY AND THE ENVIRONMENT
Abbas Ghassemi, Series Editor

INTRODUCTION TO RENEWABLE ENERGY



Vaughn Nelson

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INTRODUCTION TO

RENEWABLE ENERGY

ENERGY AND THE ENVIRONMENT

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Series Editor's Preface

By 2050, the demand for energy could double or even triple, as the global population rises and developing countries expand their economies. All life on Earth depends on energy and the cycling of carbon. Energy is essential for economic and social development but also poses an environmental challenge. We must explore all aspects of energy production and consumption including energy efficiency, clean energy, global carbon cycle, carbon sources and sinks, and biomass, as well as their relationship to climate and natural resource issues. Knowledge of energy has allowed humans to flourish in numbers unimaginable to our ancestors. The world's dependence on fossil fuels began approximately two hundred years ago. Are we running out of oil? No, but we are certainly running out of the affordable oil that has powered the world economy since the 1950s. We know how to recover fossil fuels and harvest their energy for operating power plants, planes, trains, and automobiles that result in modifying the carbon cycle and additional greenhouse gas emissions. This has resulted in the debate on availability of fossil energy resources, peak oil era and timing for the anticipated end of the fossil fuel era, and price and environmental impact versus various renewable resources and use, carbon footprint, emission and control including cap and trade and emergence of "green power."

Our current consumption has largely relied on oil for mobile applications and coal, natural gas, and nuclear or water power for stationary applications. In order to address the energy issues in a comprehensive manner, it is vital to consider the complexity of energy. Any energy resource—including oil, coal, wind, biomass, and so on—is an element of a complex supply chain and must be considered in the entirety as a system from production through consumption. All of the elements of the system are interrelated and interdependent. Oil, for example, requires consideration for interlinking of all of the elements including exploration, drilling, production, water, transportation, refining, refinery products and byproducts, waste, environmental impact, distribution, consumption/application and finally emissions. Inefficiencies in any part of the system will impact the overall system, and disruption in any one of these elements would cause major interruption in consumption. As we have experienced in the past, interrupted exploration will result in disruption in production, restricted refining and distribution, and consumption shortages; therefore, any proposed energy solution requires careful evaluation and as such, may be one of the key barriers to implement the proposed use of hydrogen as a mobile fuel.

Even though an admirable level of effort has gone into improving the efficiency of fuel sources for delivery of energy, we are faced with severe challenges on many fronts. This includes population growth, emerging economies, new and expanded usage, and limited natural resources. All energy solutions include some level of risk, including technology snafus, changes in market demand, economic drivers, and others. This is particularly true when proposing energy solutions involving implementation of untested alternative energy technologies.

There are concerns that emissions from fossil fuels will lead to climate change with possible disastrous consequences. Over the past five decades, the world's collective greenhouse gas emissions have increased significantly even as efficiency has increased, resulting in extending energy benefits to more of the population. Many propose that we improve the efficiency of energy use and conserve resources to lessen green house gas emissions and avoid a climate catastrophe. Using fossil fuels more efficiently has not reduced overall greenhouse gas emissions due to various reasons, and it is unlikely that such initiatives will have a perceptible effect on atmospheric greenhouse gas content. While there is a debatable correlation between energy use and greenhouse gas emissions, there are effective means to produce energy, even from fossil fuels, while controlling emissions. There are also emerging technologies and engineered alternatives that will actually manage the makeup of the atmosphere but will require significant understanding and careful use of energy.

We need to step back and reconsider our role and knowledge of energy use. The traditional approach of micromanagement of greenhouse gas emissions is not feasible or functional over a long period of time. More assertive methods to influence the carbon cycle are needed and will be emerging in the coming years. Modifications to the cycle means we must look at all options in managing atmospheric greenhouse gases, including various ways to produce, consume, and deal with energy. We need to be willing to face reality and search in earnest for alternative energy solutions. There appear to be technologies that could assist; however, they may not all be viable. The proposed solutions must not be in terms of a "quick approach," but a more comprehensive, long-term (10, 25, and 50 plus years) approach that is science based and utilizes aggressive research and development. The proposed solutions must be capable of being retrofitted into our existing energy chain. In the meantime, we must continually seek to increase the efficiency of converting energy into heat and power.

One of the best ways to define sustainable development is through long-term, affordable availability of resources including energy. There are many potential constraints to sustainable development. Foremost is the competition for water use in energy production, manufacturing, farming, and others versus a shortage of fresh water for consumption and development. Sustainable development is also dependent on the earth's limited amount of soil, and in the not too distant future we will have to restore and build soil as a part of sustainable development. Hence, possible solutions must be comprehensive and based on integrating our energy use with nature's management of carbon, water, and life on Earth as represented by the carbon and hydrogeological cycles. Obviously the challenges presented by the need to control atmospheric green house gases are enormous and require "out of the box" thinking, innovative approach, imagination and bold engineering initiatives in order to achieve sustainable development. We will need to ingeniously exploit even more energy and integrate its use with control of atmospheric greenhouse gases. The continued development and application of energy is essential to the development of human society in a sustainable manner through the coming centuries. All alternative energy technologies are not equal and have risks and drawbacks. When evaluating our energy options, we must consider all aspects including performance against known criteria, basic economics and benefits, efficiency, processing and utilization requirements, infrastructure requirements, subsidies and credits, waste and ecosystem, as well as unintended consequences such as impacts to natural resources and the environment. Additionally, we must include the overall changes and the emerging energy picture based on current and future efforts to modify fossil fuels and evaluate the energy return for the investment of funds and other natural resources such as water.

A significant motivation in creating this book series, which is focused on alternative energy and the environment, was brought about as a consequence of lecturing around the country and in the classroom on the subject of energy, environment, and natural resources such as water. Water is a precious commodity in the West in general and the Southwest in particular and has a significant impact on energy production, including alternative sources due to the nexus between energy and water and the major correlation with the environment and sustainability related issues. While the correlation between these elements, how they relate to each other, and the impact of one on the other are understood, it is not significantly debated on when it comes to integration and utilization of alternative energy resources into the energy matrix. Additionally, as renewable technology implementation grows by various states, nationally and internationally, the need for informed and trained human resources continues to be a significant driver in future employment resulting in universities, community colleges, and trade schools offering minors, certificate programs, and even, in some cases, majors in renewable energy and sustainability. As the field grows, the demand for trained operators, engineers, designers, and architects that would be able to incorporate these technologies into their daily activity is increasing. Additionally, we receive daily deluge of flyers, emails, and texts on various short courses available for interested parties in solar, wind, geothermal, biomass, and so on under the umbrella of retooling an individual's career and providing trained resources needed to interact with financial, governmental, and industrial organizations.

In all my interactions throughout the years in this field, I have conducted significant searches in locating integrated textbooks that explain alternative energy resources in a suitable manner and that would complement a syllabus for a potential course to be taught at the university while providing good reference material for people interested in this field. I have been able to locate a number of books on the subject matter related to energy, energy systems, resources such as fossil nuclear, renewable and energy conversion, as well as specific books in the subjects of natural resource availability, use, and impact as related to energy and the environment. However, specific books that are correlated and present the various subjects in detail are few and far between. We have therefore started a series of texts, each addressing specific technology fields in the renewable energy arena. As a part of this series, there are textbooks on wind, solar, geothermal, biomass, hydro, and others yet to be developed. Our texts are intended for upper-level undergraduate and graduate students and for informed readers who have a solid fundamental understanding of science and mathematics as well as individuals/organizations that are involved with design development of the renewable energy field entities that are interested in having reference material available to their scientists and engineers, consulting organizations, and reference libraries. Each book presents fundamentals as well as a series of numerical and conceptual problems designed to stimulate creative thinking and problem solving.

The series author wishes to express his deep gratitude to his wife Maryam who has served as a motivator and intellectual companion and too often was victim of this effort. Her support, encouragement, patience, and involvement have been essential to the completion of this series.

Abbas Ghassemi, PhD
Las Cruces, New Mexico

Preface

The big question: How do we use science and technology such that spaceship Earth will be a place for all life to exist? We are citizens of the planet Earth, and within your lifetime there will major decisions regarding the following: energy (includes food), water, minerals, space, and war (which I can state will happen with 99.9% probability). This statement was written over 20 years ago when I first taught introductory courses on wind and solar energy. Since then, the United States has been involved in a number of armed conflicts, so the prediction on war was easily fulfilled. Armed conflicts over resources have already started, Oil War I (Gulf War) and Oil War II (Iraq war), and a sustainable energy future primarily fueled by renewable energy is paramount to reduce the possibility of Oil War III with China over dwindling supplies of petroleum. This is also the opinion of one of my Chinese colleagues working in renewable energy.

We are over 6 billion and heading toward 11 billion people, and we are all part of an uncontrolled experiment on the effect of human activities on the Earth's environment. Renewable energy is part of the solution for the energy dilemma of finite resources of fossil fuels and the environmental impact from greenhouse gases. Renewable energy is now part of national policies, with goals that have renewable energy a significant percentage of generated energy within the next decades. The reasons are that there is a large amount of renewable energy in all parts of the world in contrast to fossil fuels and minerals, it is sustainable, and it reduces greenhouse gas emissions. The growth of renewable energy has been large, 20% per year and more, because the starting point was small, except for large hydroelectric installations, whose growth is around 2% per year. The installed capacity for the generation of electricity by renewable energy is still led by hydroelectricity at 850 GW; however, wind power is now over 158 GW (a significant part of new electric plant capacity from all sources) and photovoltaics (PV) is over 23 GW.

Acknowledgments

I am deeply indebted to colleagues, present and past, at the Alternative Energy Institute (AEI) at West Texas A&M University (WTAMU), and the Wind Energy Group at the Agricultural Research Service (ARS), U.S. Department of Agriculture, Bushland, Texas. The students in my classes and the students who have worked at AEI have provided insight and feedback. There are many others who have worked with us at AEI and ARS, especially the numerous international researchers and interns. Thanks to Instructional Technology Services, WTAMU, for the computer drawings. I want to express gratitude to my wife Beth, who has put up with me all these years.

About the Author

Dr. Vaughn Nelson has been involved with renewable energy, primarily wind energy, since the early 1970s; is the author of six books (five books on CD); has published over 50 articles and reports; was the principal investigator on numerous grants; and has given over 60 workshops and seminars from the local to international level. Primary work has been on wind resource assessment, education and training, applied research and development, and rural applications of wind energy. Presently, he is a research professor with the Alternative Energy Institute (AEI), West Texas A&M University (WTAMU). He was director of AEI from its inception in 1977 through 2003 and then returned for another year in July 2009. He retired as dean of the Graduate School, Research and Information Technology, WTAMU, in 2001. He served on state of Texas committees, most notably the Texas Energy Coordination Council during its 11 years. He has received three awards from the American Wind Energy Association, one of which was the Lifetime Achievement Award in 2003; received an award as a Texas Wind Legend in 2010 from the Texas Renewable Industries Association; and served on the board of directors for state and national renewable energy organizations. One of the projects was a renewable energy demonstration building at the AEI Wind Test Center (details are provided in this book). Dr. Nelson developed the material for a new online course in renewable energy at WTAMU, spring 2010, and this book is the result. Dr. Nelson is also the author of *Wind Energy, Renewable Energy and the Environment* (CRC Press, Boca Raton, FL, 2009).

Dr. Nelson holds a PhD in physics from the University of Kansas; an EdM from Harvard University; and a BSE from Kansas State Teachers College, Emporia. He was at the Departamento de Física, Universidad de Oriente, Cumana, Venezuela, for 2 years and then at WTAMU from 1969 to the present.

1 Introduction

1.1 ENERGY AND SOCIETY

Industrialized societies run on energy, a tautological statement in the sense that it is obvious. Population, gross domestic product (GDP), consumption, and production of energy and production of pollution for the world and the United States are interrelated. The United States has less than 5% of the population of the world; however, in the world, the United States generates around 25% of the gross production and 22% of the carbon dioxide emissions and is at 22% for energy consumption (Figure 1.1). Notice that the countries listed in Figure 1.1 consume around 75% of the energy and produce 75% of the world GDP and carbon dioxide emissions. The developed countries consume the most energy and produce the most pollution, primarily due to the increase in the amount of energy per person. On a per person basis, the United States is the worst for energy consumption and carbon dioxide emitted.

The energy consumption in the United States increased from 32 quads in 1950 to 101 quads in 2009. One quad is equal to 10^{15} British thermal units (Btu). There was an increase in efficiency in the industrial sector, primarily due to the shock of the oil crisis of 1973. However, you must remember that correlation between GDP and energy consumption does not mean cause and effect. The oil crisis of 1973 showed that efficiency is a major component in gross national product and the use of energy.

It is enlightening to consider how the United States has changed in terms of energy use since World War II. Ask older individuals about their lives in the 1950s and then compare the following with today:

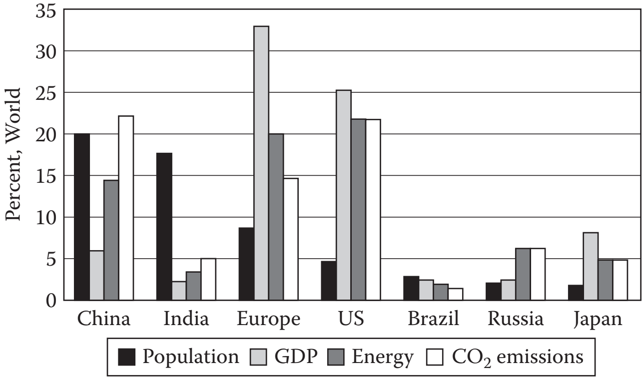

FIGURE 1.1 Comparisons, percentage of world, for population (rank in world), gross domestic product, energy consumption, and carbon dioxide emission.

Residential: space heating and cooling, number of lights, amount of space per person
Transportation: number and types of vehicles in the family
Commercial: space heating and cooling for buildings, lights
Industrial: efficiency

A thought on energy and GDP: Solar clothes drying (a clothesline) does not add to the GDP, but every electric and gas dryer contributes; however, they both do the same function. We may need to think in terms of results and efficient ways to accomplish a function or process and the actual life-cycle cost. Why do we need heavy cars or sport utility vehicles with big motors that accelerate rapidly to transport people?

Now, the underdeveloped part of the world, primarily the two largest countries in terms of population (China $1.3 * 10^9$ and India $1.1 * 10^9$) are beginning to emulate the developed countries in terms of consumption of energy, consumption of material resources, and greenhouse gas emissions. One dilemma in the developing world is that a large number of villages and others in rural areas do not have electricity.

1.2 TYPES OF ENERGY

There are many different types of energy. Kinetic energy is energy available in the motion of particles (e.g., wind or moving water). Potential energy is the energy available because of the position between particles, for example, water stored in a dam, the energy in a coiled spring, and energy stored in molecules (gasoline). There are many examples of energy: mechanical, electrical, thermal (heat), chemical, magnetic, nuclear, biological, tidal, geothermal, and so on.

In reality, there are only four generalized interactions (forces between particles) in the universe: nuclear, electromagnetic, weak, and gravitational [1]. In other words, all the different types of energy in the universe can be traced back to one of these four interactions (Table 1.1). This interaction or force is transmitted by an exchange particle. The exchange particles for electromagnetic and gravitational interactions have zero rest mass, so the transfer of energy and information is at the speed of light, $3 * 10^8$ m/s (186,000 mi/s). Even though the gravitational interaction is extremely weak, it is noticeable when there are large masses. The four interactions are a great example of how a scientific principle covers an immense number of phenomena.

TABLE 1.1
Information for Generalized Interactions

Interaction	Particle	Strength	Range (m)	Exchange Particle
Nuclear (strong)	Quarks	1	10^{-15}	Gluons
Electromagnetic	Charge	10^{-2}	Infinite	Photon
Weak	Leptons	10^{-6}	10^{-18}	Weakons[a]
Gravitational	Mass	10^{-39}	Infinite	Graviton

[a] My name for exchange particles (intermediate vector bosons).

The source of solar energy is the nuclear interactions at the core of the sun, where the energy comes from the conversion of hydrogen nuclei into helium nuclei. This energy is primarily transmitted to the Earth by electromagnetic waves, which can also be represented by particles (photons). In this course, we deal primarily with the electromagnetic interaction, although hydro and tides are energy due to the gravitational interaction, and geothermal energy is due to gravitational and nuclear decay.

We use exponents to indicate large and small numbers. The exponent indicates how many times the number is multiplied by itself or how many places the decimal point needs to be moved. Powers of ten are useful in order of magnitude problems, which are rough estimates.

$$10^3 = 10 * 10 * 10 = 1{,}000$$

$$10^{-3} = 1/10^3 = 0.001$$

Note that there is a discrepancy between the use of billions in the United States (10^9) and England (10^{12}). If there is a doubt, we use exponents or the following notation for prefixes:

nano	10^{-9}	giga	10^9
micro	10^{-6}	tera	10^{12}
milli	10^{-3}	peta	10^{15}
		exa	10^{18}
kilo	10^3		
mega	10^6	quad	10^{15} Btu

1 quad = 1.055 exajoules

1.3 RENEWABLE ENERGY

Solar energy is referred to as *renewable* or *sustainable* energy because it will be available as long as the sun continues to shine. Estimates for the remaining life of the main stage of the sun are another 4 to 5 billion years. The energy from the sun, electromagnetic radiation, is referred to as *insolation*. The other main renewable energies are wind, bioenergy, geothermal, hydro, tides, and waves. Wind energy is derived from the uneven heating of the surface of the Earth due to more heat input at the equator with the accompanying transfer of water and thermal energy by evaporation and precipitation. In this sense, rivers and dams for hydro energy are stored solar energy. The third major aspect of solar energy is the conversion of solar energy into biomass by photosynthesis. Animal products such as oil from fat and biogas from manure are derived from solar energy. Another renewable energy is geothermal energy due to heat from the Earth from decay of radioactive particles and residual heat from gravitation during formation of the Earth. Volcanoes are fiery examples of geothermal energy reaching the surface from the interior, which is hotter than the surface. Tidal energy is primarily due to the gravitational interaction of the Earth and the moon.

Overall 14% of the world's energy comes from bioenergy, primarily wood and charcoal but also crop residue and even animal dung for cooking and some heating. This contributes to deforestation and the loss of topsoil in developing countries. Production of ethanol from biomass is now a contributor to liquid fuels for transportation, especially in Brazil and the United States.

In contrast, fossil fuels are stored solar energy from past geological ages. Even though the quantities of oil, natural gas, and coal are large, they are finite, and for the long term of hundreds of years, they are not sustainable.

1.4 ADVANTAGES/DISADVANTAGES

The advantages of renewable energy are that they are sustainable (nondepletable), ubiquitous (found everywhere across the world, in contrast to fossil fuels and minerals), and essentially nonpolluting. Note that wind turbines and photovoltaic panels do not need water for the generation of electricity, in contrast to steam plants fired by fossil fuels and nuclear power.

The disadvantages of renewable energy are variability and low density, which in general results in higher initial cost. For different forms of renewable energy, other disadvantages or perceived problems are visual pollution, odor from biomass, avian and bat mortality with wind turbines, and brine from geothermal energy. Wherever a large renewable facility is to be located, there will be perceived and real problems to the local people. For conventional power plants using fossil fuels, for nuclear energy, and even for renewable energy, there is the problem of "not in my backyard."

1.5 ECONOMICS

Business entities always couch their concerns in terms of economics (money), such as "We cannot have a clean environment because it is uneconomical." The thought here is that renewable energy is not economical in comparison to coal, oil, and natural gas. We must be allowed to continue our operations as in the past because if we have to install new equipment to reduce greenhouse gas emissions, we cannot compete with other energy sources, and finally we will have to reduce employment, jobs will go overseas, and so on.

The different types of economics to consider are pecuniary, social, and physical. *Pecuniary* is what everybody thinks of as economics, *money*. On that note, we should be looking at life-cycle costs rather than our ordinary way of doing business, low initial costs. Life-cycle costs refer to all costs over the lifetime of the system.

Social economics are those borne by everybody, and many businesses want the general public to pay for their environmental costs. A good example is the use of coal in China, where there are laws (social) for clean air, but they are not enforced. The cost will be paid in the future in terms of health problems, especially for the children today. If environmental problems affect someone else today or in the future, who pays? The estimates of the pollution costs for generation of electricity by coal range from $0.005 to $0.10/kWh.

Physical economics is the energy cost and the efficiency of the process. There are fundamental limitations in nature due to physical laws. *Energetics*, which is the energy input versus energy in the final product for any source, should be positive. For example, production of ethanol from irrigated corn has close to zero energetics. So, physical economics is the final arbitrator in energy production and consumption. In the end, *Mother Nature always wins,* or the corollary, pay now or probably pay more in the future.

Finally, we should look at incentives and penalties for the energy entities. What each entity wants are subsidies for itself and penalties for its competitors. Penalties come in the form of taxes and environmental and other regulations, while incentives come in the form of subsidies, breaks on taxes, lack of social costs to pay on the product, and governmental funding of research and development. How much should we subsidize businesses for exporting overseas? It is estimated that we use energy sources in direct proportion to the incentives that source has received in the past. There are many examples of incentives and penalties for all types of energy production and use.

1.6 GLOBAL WARMING

Global warming is a good example that physical phenomena do not react to political or economic statements. Global warming is primarily due to human activity.

"Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (see Figure SPM.1). The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture" [2, Summary for Policy Makers, p. 2].

Concentrations of carbon dioxide in the atmosphere (Figure 1.2) are projected to double with future energy use based on today's trend [3,4].

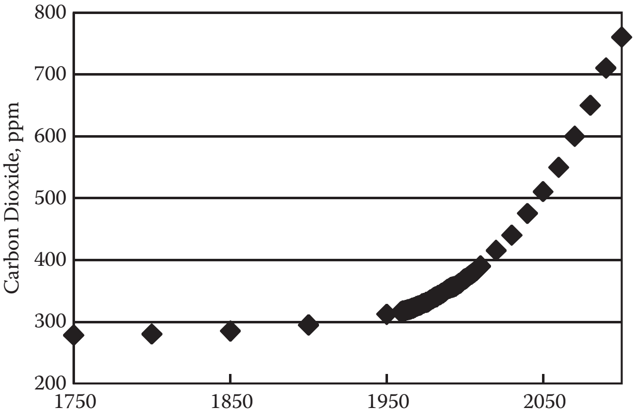

FIGURE 1.2 Carbon dioxide in the atmosphere and projected growth with no emission reductions.

The Kyoto Protocol of 1996 to reduce greenhouse gas emissions became effective in 2005 as Russia became the 55th country to ratify the agreement. The goal was for the participants collectively to reduce emissions of greenhouse gases by 5.2% below the emission levels of 1990 by 2012. While the 5.2% figure was a collective one, individual countries were assigned higher or lower targets, and some countries were permitted increases. For example, the United States was expected to reduce emissions by 7%. However, this did not happen as the United States did not ratify the treaty because the perceived economic costs would be too large, and there were not enough provisions for developing countries, especially China, to reduce future emissions.

If participant countries continue with emissions above the targets, then they are required to engage in emissions trading. Notably, participating countries in Europe are using different methods for carbon dioxide trading, including wind farms and planting forests in other countries. Carbon dioxide emissions will still increase, even if nations reduce their emissions to 1990 levels, because of population growth and increase in energy use in the underdeveloped world. As the Arctic thaws, then methane, a more potent greenhouse gas than CO^2, would further increase global warming [5].

Increased temperatures and the effect on weather and sea-level rise are the major consequences. Overall, the increased temperature will have negative effects compared to the climate of 1900–2000. By 2100, sea levels are projected to increase by 0.2 to 1 m, with an increase of 2 m unlikely but physically possible. With positive feedback due to less sea ice and continued increase in carbon dioxide emissions, then melting of the Greenland ice sheets would increase the sea level by over 7 m, and the West Antarctic Ice Sheet would add another 5 m. The large cities on the oceans will have to be relocated or build massive infrastructures to keep out the ocean. Who will pay for this, national or local governments?

1.7 ORDER OF MAGNITUDE ESTIMATES

In terms of energy consumption, production, supply and demand, and design for heating and cooling, estimates are needed, and an order of magnitude estimate will suffice. By order of magnitude, we mean an answer to within a power of ten.

Example 1.1

How many seconds in a year. With a calculator, it is easy to determine:

$$365 \text{ days} * 24 \text{ h/day} * 60 \text{ min/h} * 60 \text{ s/h} = 31{,}536{,}000$$

When you round to one significant digit, this becomes $3 * 10^7$ seconds.

For an order of magnitude estimate for this multiplication, round each number with a power of ten, then multiply numbers and add the powers of ten:

$$4 * 10^2 * 2 * 10^1 * 6 * 10^1 * 6 * 10^1 = 4 * 2 * 6 * 6 * 10^5$$

$$= 288 * 10^5 = 3 * 10^2 * 10^5 = 3 * 10^7 \text{ s.}$$

1.8 GROWTH (EXPONENTIAL)

Our energy dilemma can be analyzed in terms of fundamental principles. It is a physical impossibility to have exponential growth of any product or exponential consumption of any physical resource in a finite system. As an example, suppose Mary started employment at \$1/yr; however, her salary is doubled every year, a 100% increase (Table 1.2, Figure 1.3). Notice that after 30 years, her salary is \$1 billion. Also, notice that for any year, the amount needed for the next period is equal to the total sum for all the previous periods plus one. The mathematics of exponential growth is given in Appendix 1.

Another useful idea is doubling time, $T2$ for exponential growth, which can be calculated by

$$T2 = 69/R \tag{1.1}$$

TABLE 1.2
Exponential Growth with a Doubling Time of 1 Year

Year	Salary (\$)	Amount = 2^t	Cumulative (\$)
0	1	2^0	1
1	2	2^1	3
2	4	2^2	7
3	8	2^3	15
4	16	2^4	31
5	32	2^5	63
t		2^t	$2^{t+1}-1$
30	$1*10^9$	2^{30}	$2^{31}-1$

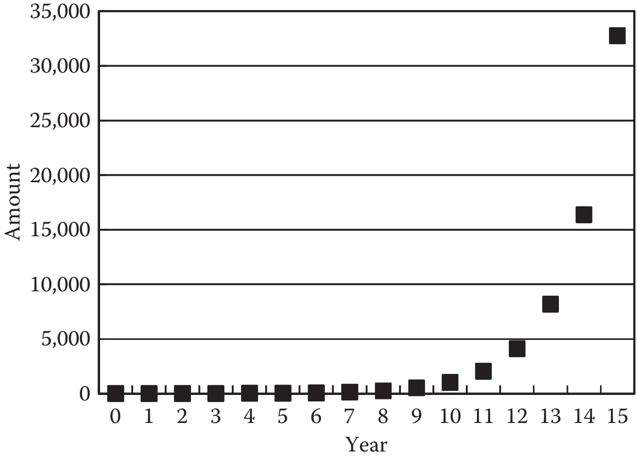

FIGURE 1.3 Salary with a doubling time of 1 year to show exponential growth.

TABLE 1.3
Doubling Times for Different Rates of Growth

Growth (%/year)	Doubling Time (years)
1	69
2	35
3	23
4	18
5	14
6	12
7	10
8	8
9	8
10	7
15	5

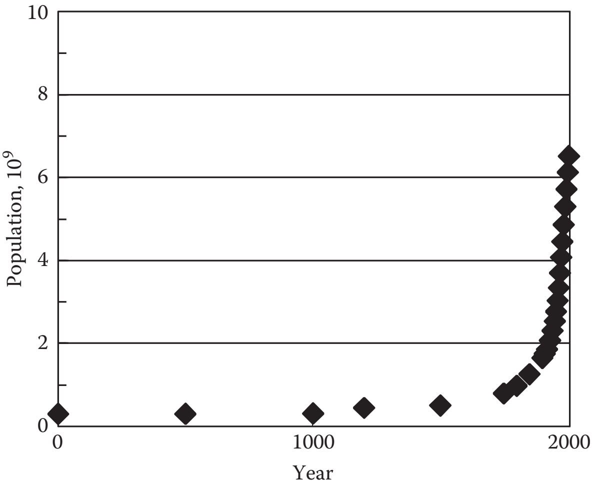

FIGURE 1.4 World population showing exponential growth.

where *R* is the percentage growth per unit time. Doubling times for some different year rates are given in Table 1.3.

There are numerous historical examples of growth; population, 2–3%/yr; gasoline consumption, 3%/yr; world production of oil, 5–7%/yr; electrical consumption, 7%/yr. If we plotted the value per year for smaller rates of growth (Figure 1.4), the curve would be the same as in Figure 1.3, only the timescale along the bottom would be different. The U.N. projects over 9 billion people (Figure 1.5) by 2050 [6], with the assumption that the growth rate will decrease from 1.18% in 2008 to 0.34% in 2050.

However, even with different rates of growth, the final result is still the same. *When consumption grows exponentially, enormous resources do not last long.*

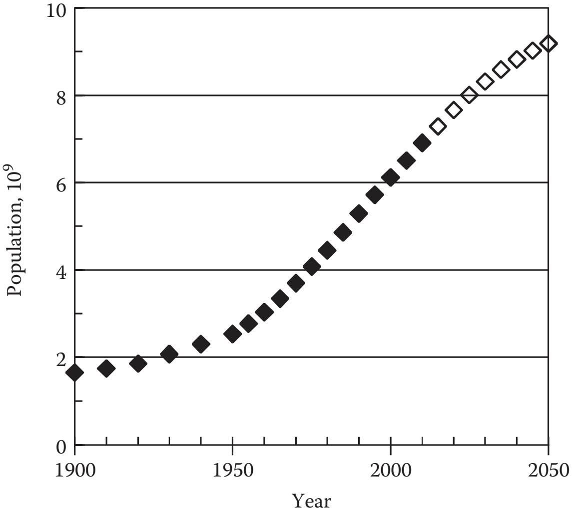

FIGURE 1.5 World population with projection to 2050 under median variant.

This is the fundamental flaw in term of ordinary economics (dollars) and announcing growth in terms of percentages. How long do they want those growth rates to continue? Nobody wants to discuss how much is enough. The theme since President Reagan is that all we need is economic development, and the world's problems will be solved. However, the global economic crisis of 2008 and environmental problems have made some economists have second thoughts on continued growth. Now, there are many books on the problems of fossil fuels, other resources such as minerals and water, and environmental effects.

1.9 SOLUTIONS

We do not have an energy crisis since you will learn energy cannot be created or destroyed. We have an energy dilemma because of the finite amount of readily available fossil fuels, which are our main energy source today. The problem is twofold: overpopulation and overconsumption. Population is $6.8 * 10^9$ and growing toward $9 * 10^9$ and maybe even larger, and developing countries want the same standard of living as developed countries. The world population is so large that we are doing an uncontrolled experiment on the environment of the Earth. However, the developed countries were also major contributors to this uncontrolled experiment in terms of consumption, and now increased consumption in China and India is adding to the problem.

The solution depends on world, national, and local policies and what policies to implement and even individual actions. In my opinion, it is obvious what needs to be done for the world: reduce consumption, have zero population growth, shift to renewable energy, reduce greenhouse gas emissions, reduce environmental pollution, and reduce military expenditures. What do you do as an individual? I have done things in the past to save energy and have future plans. What are yours?

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6. United Nations. 2008. World population prospects, the 2008 revision, highlights. http://www.un.org/esa/population/publications/wpp2008/wpp2008_highlights.pdf.

RECOMMENDED RESOURCES

LINKS: GENERAL

Energy Information Administration, U.S. Department of Energy. http://www.eia.doe.gov. This site contains a lot of information on U.S. and international energy resources and production. International energy outlook, http://www.eia.doe.gov/iea/. Data files can be downloaded (PDFs and spreadsheets).

United Nations. Information on population and projections on population. http://www.un.org/esa/population/unpop.htm.

U.S. Census. U.S., world population clocks. http://www.census.gov.

LINKS: GLOBAL WARMING

Global Climate Change Impacts Report, June 2009. http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts.

Intergovernmental Panel on Climate Change. http://www.ipcc.ch.

Union of Concerned Scientists, Global Warming. http://www.ucsusa.org/global_warming.

United States Global Change Research Program. http://www.globalchange.gov.

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PROBLEMS

1. What was the population of the world in 1950, 2000, and this year, and what is projected for 2050?
2. What was the population of your country in 1950, 2000, and this year, and what is projected for 2050?
3. List two advantages of renewable energy.
4. List two disadvantages of renewable energy.
5. Besides large hydro, what are the two most important renewable energy sources for your country?
6. For a sustainable society in your country, what would be the two most important policy issues?
7. What are the largest two sources for carbon dioxide emissions?
8. Besides the United States, what country consumes the most energy?
9. What country emits the most carbon dioxide?
10. The size of the European Union has increased over the years. Estimate the percentage increase in GDP and energy consumption by the addition of these new blocks of countries.
11. When is gravity considered a source for renewable energy?
12. Global warming is primarily due to what factor?
13. What is the predicted amount of carbon dioxide (ppm) in the atmosphere for 2050?
14. What two nations emit the most carbon dioxide per year? What percentage is that of the total for the world?
15. What percentages of the total for the world of carbon dioxide emission per year is due to combustion of coal, combustion of oil, combustion of natural gas?
16. What is your carbon footprint? Calculators are available on the Internet, for example http://www.carbonify.com/carbon-calculator.htm or http://www.carbonfootprint.com/calculator1.html.
17. Under the Kyoto Protocol, list three participating countries and their emission levels of carbon dioxide (latest year available) compared with their levels in 1990. Remember the target levels are below 1990 levels.
18. The local businesspeople want the city to grow. What rate do they want (%/year)? What is that doubling time?
19. Suppose world population grows at 0.5% per year. What is the doubling time? After that period of time, what is the projected world population?

2 Energy

2.1 INTRODUCTION

Scientists have been successful in understanding and finding unifying principles. However, many people take the resulting technology for granted and do not understand the limitations of humans as part of the physical world. There are moral laws (or principles), civil laws, and physical laws. Moral laws have been broken (e.g., murder and adultery), civil laws have been broken (almost everybody has driven over the speed limit), *but nobody breaks a physical law*. Therefore, we can only work with nature, and we cannot do anything that violates the physical world.

We have been and we will be clever in manipulating and using physical laws in terms of science and the application of science, technology. Just think over the past century, from first flight of airplanes (1903), to man landing on the moon (1969), and to exploration of the solar system by robotic systems, and from the special theory of relativity (1905) which predicted the relation between mass and energy to the atomic bomb (1945). Another major technology advance is the invention of the transistor (1947), which led to integrated circuits and myriad electronic devices; as a result, much of the population of the world (2010) has instant mobile phones, songs, and video in their hands and via Internet access.

A major unifying concept is energy and how energy is transferred. The area that deals with heat, a form of energy, is called *thermodynamics*.

2.2 DEFINITION OF ENERGY AND POWER

To understand renewable energy, the definitions of energy and power are needed. *Work* is the force on an object, which is then moved through some distance.

$$\text{Work} = \text{Force} * \text{Distance}$$

or

$$W = F * D\text{, joule (J), J = newton (N) meter (m)} \tag{2.1}$$

A number of symbols are used, and with the easy availability of personal computers and calculators, sample calculations are used for illustration and understanding. Many people have a mental block as soon as they see mathematical symbols, but everybody uses symbols. Therefore, Equation 2.1 can be understood as a shorthand notation for the words and concepts written that preceded it.

Moving objects, doing work, and changing position between interacting particles requires energy, so energy and work are measured by the same units. Some units of energy are the joule, calorie, kilowatt hour (kWh), Btu, quad.

Calorie = Amount of energy required to raise 1 g water 1°C

British thermal unit (Btu) = Amount of energy required to raise 1 pound of water 1°F

Some conversion factors for energy are as follows:

1 cal = 4.12 J

Calorie = Kilocalorie, the unit used in nutrition = 1,000 calories

1 Btu = 1,055 J

$$1 \text{ barrel of oil (42 gal)} = 6.12 \times 10^9 \text{ J} = 1.7 \times 10^3 \text{ kWh}$$

$$1 \text{ ton of coal} = 2.5 \times 10^7 \text{ Btu} = 2.2 \times 10^{10} \text{ J}$$

$$1 \text{ quad} = 10^{15} \text{ Btu} = 1.055 \text{ exajoules}$$

$$1 \text{ kWh} = 3.6 \times 10^6 \text{ J}$$

Objects in motion can do work; therefore, they possess energy, kinetic energy (KE):

$$\text{KE} = 0.5\, mv^2 \tag{2.2}$$

where m is the mass of the object, and v is its speed.

Example 2.1

A car with a mass of 1,000 kg moving at 10 m/s has the following kinetic energy:

$$\text{KE} = 0.5 * 1{,}000 * 10 * 10 \text{ kg (m/s)}^2 = 5{,}000 \text{ J}$$

Remember in calculations, units are required.

Because objects interact (e.g., by gravity), then due to their relative position they can do work or have energy, potential energy (PE). To raise a 10 kg mass a height of 2 m requires 200 J of energy. You are changing the gravitational potential energy, so at that upper level, that object has 200 J of potential energy.

Power is the rate of energy use or production.

$$\text{Power} = \text{Energy/time, joule/second} = \text{Watt} \tag{2.3}$$

If power is known, then energy can be calculated for any time period.

$$E = P * t \tag{2.4}$$

A kilowatt (kW) is a measure of power, and a kilowatt hour (kWh) is a measure of energy. Motors (kW or horsepower) and power plants (megawatts) are rated in terms of power.

Example 2.2

A 5-kW electric motor, which runs for 2 h, consumes 10 kWh of energy.

Example 2.3

Eight 100-W lightbulbs that are left on all day will consume 8 * 100 * 24 = 19,300 Wh = 19.3 kWh of energy.

2.3 HEAT

Heat is another form of energy, thermal energy. Heat is just the internal kinetic energy (random motion of the atoms) of a body. Rub your hands together, and they get warmer. As you heat your home, you are increasing the speed of the air particles. *Heat and temperature are different.* Heat is energy, and temperature is the potential for transfer of heat from a hot place to a cold place. In the transfer of this heat, work can be done. As an example of the difference between heat and temperature: Would you rather stick your finger in a cup of hot coffee, $T = 80°\text{C}$, or get hit by a high-speed proton, $T = 1{,}000{,}000°\text{C}$? One has much more energy than the other does.

2.4 THERMODYNAMICS

The understanding of energy today can be embodied in the following laws or principles of thermodynamics.

1. Energy is conserved. Energy is not created or destroyed, only transformed from one form to another. In layperson's terms, this means that all you can do is break even. A number of patents have been issued for perpetual motion machines [1], a device that produces more energy than the energy needed to run the machine. A number of people have invested money in such machines, but needless to say, the money was lost since the devices contradict the first law of thermodynamics.
2. Thermal energy, heat, cannot be transformed totally into work. In simpler terms, you cannot even break even. Another way of looking at it is that systems tend toward disorder, and in transformations of energy, disorder increases. As entropy is a measure of order, then in succinct terms, entropy is increasing.

This means that some forms of energy are more useful than other forms. For example, the energy in a gallon of gasoline is not lost but only transformed into heat by a car. However, after the transformation, that energy is dispersed into a low-grade form (more entropy) and cannot be used to do more work in moving the car.

As an aside for the scientists, the following most famous equation says that mass is just a concentrated form of energy. Conversion of a small amount of mass gives a lot of energy (e.g., an atomic or hydrogen bomb).

$$E = mc^2$$

where c is the speed of light.

2.5 ENERGY DILEMMA IN LIGHT OF THE LAWS OF THERMODYNAMICS

As energy cannot be created or destroyed, only transferred, we have an energy dilemma in the use of energy resources and their effect on the environment. Therefore, *the first and primary objective of any energy policy must be conservation and efficiency*, as that is the most economic use of a barrel of oil and less expensive than drilling for new oil.

2.5.1 CONSERVATION

Conservation means if you do not need it, do not turn it on or use it. President Carter's admonition to reduce the thermostat setting and setting a speed limit of 55 mph were conservation measures. High prices and shortages (e.g., in the California electrical crisis of 2000–2001) increase conservation, and the high price of gasoline in 2008 made more people consider fuel efficiency before they purchased a vehicle. In general, utility companies like to sell more electricity rather than have customers save energy.

2.5.2 EFFICIENCY

Efficiency is measure of energy for the function or product divided by the energy input.

$$\text{Efficiency} = \text{Energy out}/\text{Energy in}$$

Energy can be used to do work (mechanical energy) and to heat an object or space (thermal energy) and be transformed to electrical energy or stored as potential energy. In each transformation, an upper limit on efficiency can be determined by the second law of thermodynamics. In thermal processes, this efficiency is determined by the temperatures of the hot and cold reservoirs.

$$Eff = \frac{T_H - T_C}{T_H} \tag{2.5}$$

Temperatures must be in degrees Kelvin, $T_{\text{deg K}} = T_{\text{deg C}} + 273$.

In an electrical generating plant that uses steam at 700°C (973 K) and on the downside is cooled by water to 300°C (573 K), the maximum efficiency possible is around 0.41 or 41%. Modern thermal power plants have efficiencies of around 40%. In other words, 60% of the stored chemical (or nuclear) energy is rejected and 40% is converted into electricity.

Temperature is a measure of potential for heat transfer and is not a measure of energy. Since efficiency is always less than 1, for a system or device to continue to operate, energy must be obtained from outside the system. For every energy transformation, there is an efficiency, and the total efficiency is the product of the individual efficiencies (multiply). The efficiency of converting coal to light using incandescent lightbulbs is around 2%.

Transformation	**Efficiency, %**
Mining of coal	96
Transportation of coal	97
Generation of electricity	38
Transmission of electricity	93
Incandescent bulb (electricity to light)	5
Overall efficiency (coal to light)	1.6

Therefore, fluorescent lights (15–25% efficiency) for commercial buildings and compact fluorescent lights for your home are important. Now, light-emitting diodes (LEDs) (25–50% efficiency) are available. Countries, states, and even cities are setting regulations to phase out incandescent lighting. This also says that daylighting can save money, especially during the summer as you do not need air conditioning to reduce the heat given off by lights.

As a corollary to the second law efficiency, a system for producing energy must be a net energy gainer, the energetics of the system. In the physical world, subsidies or economics (dollars) do not change the energetics of the systems for production of energy; all they do is tilt consumption or use in favor of different energy resources. For example, at some point in the future it will take more energy to drill for oil than the amount of energy in the oil produced. At that point, it would be foolish to subsidize the drilling for oil as an energy source. It might be that the product is so useful as a liquid fuel or as a source for other products that it could be subsidized by other energy sources. How much natural gas does it take to produce oil from tar sands in Canada? What is the energetics of producing ethanol from corn?

Prior to the oil crisis of 1973, industry and business maintained that efficiency was not cost effective, and that gross domestic product (GDP) was tied directly to the use of energy. Industry changed, and the United States saved thousands of millions (10^9) of dollars since 1973 by increased efficiency in industry and higher efficiency for transportation. However, as stated, much more has to be accomplished by conservation and increasing efficiency.

An example of efficiency is cogeneration, today referred to as combined heat and power. In the production of electricity, the low-grade (lower-temperature) energy can be used for other processes. In most electric power plants where electricity is generated by steam (coal, oil, gas, and even nuclear), 60% of the heat is not used. Combined cycle gas turbines have higher efficiencies as heat from the first cycle is also used. In Europe, some electric power plants have heating districts associated with them.

Efficiency in transportation is an example of the difficulty in formulating a rational energy policy that would convert the world to sustainable energy within the environmental limitations. Every U.S. president since 1973 has called for energy independence, primarily due to the high cost of imported oil. The high price for oil in 2008 and then the financial crisis with the automobile industry needing government money to operate in 2009 demonstrate the failure of past energy policies. In 2006, President G. W. Bush's energy policy was to drill for more oil and gas, and as in the past, the automobile industry fought against increasing fuel efficiency. The argument was again couched in terms of economics: Because we cannot compete with foreign manufacturers of small cars, consumers will not buy fuel-efficient cars (advertising advocates large motors, heavy sport utility vehicles [SUVs], and large vehicles for safety). In past discussions with students, they stated that gasoline in the United States would have to be around $1/L ($4/gal) before they would buy a fuel-efficient vehicle. Of course, Europeans and people in other countries have been paying those and even higher prices for a long period. Couched in terms of the safety issue, everybody should drive a semitruck (to heck with fuel efficiency), or at least we all deserve big Hummers. Another note is that vehicles powered by fuel cells using hydrogen are much more efficient than those with internal combustion engines. Why do we not have millions of those vehicles on the road today?

Looking back, the obvious answer was to increase fuel efficiency and mandate a substantial tax on gasoline after the oil crisis of 1973. There was progress on fuel efficiency as in 1975 the U.S. Congress passed laws for combined automobile fleet efficiency (CAFE) for vehicles weighing less than 3,886 kg; however, pickups and large vans did not count in the CAFE requirements. This law has saved the United States billions of dollars in imported oil. The problem was that SUVs were counted as light trucks, and their fuel consumption was around 5.5 km/L (12 mpg), so the overall fuel efficiency declined as SUVs gained market share. In 1999, over half a million vehicles sold exceeded the gross vehicle weight requirements. Even with continued objections by the automobile industry and reluctant acceptance by the G. W. Bush administration, finally in 2007 CAFE was revised to eliminate the exemptions to light trucks classified as SUVs or passenger vans unless they exceed 4,500 kg gross vehicle weight, and the CAFE was increased to 15 km/L (35 mpg) by the year 2020. The United States and Canada have the lowest standards in terms of CAFE and the toughest emissions requirements among developed nations, while the European Union and Japan have higher fuel economy standards but have lower emission standards.

President Obama is touting efficiency and renewable energy. The question remains whether the policies will be stringent enough to make an impact on oil consumption and greenhouse gas emissions. U.S. federal tax credits (2009) include a new tax credit, starting at $2,500 and capped at $7,500, for plug-in hybrid electric vehicles. The first 250,000 vehicles sold by each manufacturer get the full tax credit, and then it phases out like the hybrid vehicle tax credits were phased out with more vehicles sold.

In an interesting note, the big three automobile manufacturers in the United States received over $\$2 * 10^9$ in research and development (R&D) funding from the government for the Partnership for New Generation of Vehicles [2]. The goal was to create a sedan for five people that would obtain 80 mpg. The manufacturers said that there is no way to reach that goal; however, they wanted money to build more efficient cars and even obtained tax breaks for a limited time period for people trading in old, inefficient cars ("cash for clunkers"). Again, the question concerns where the federal government should place these incentives. It would be cheaper to subsidize more efficient cars than to pay all the costs for imported oil. What is the additional cost for imported oil if the military costs for the Oil War I (Gulf War) and the Oil War II (Iraq war) are included? A $0.50 tax on a gallon of gasoline would just about pay for Oil War II and the war in Afghanistan and would help drive purchases of more efficient cars.

The Organization of Petroleum Exporting Countries (OPEC) wants to keep the price of oil in the range at which they make a lot of money, but not so high it encourages conservation and efficiency. However, *at some point the demand for oil across the world will be higher than can be supplied*. When production starts to decline, we will have higher prices, which will surpass the high prices of 2008.

2.6 USE OF FOSSIL FUELS

The night sky of Earth taken by satellite illustrates the tremendous amount of energy radiating into space from lights and fires [3]. In 2009, world consumption of energy was around 520 exajoules (EJ), with the United States and Europe accounting for almost 40% of the total; with the addition of only four other nations, the amount is 70% (Figure 2.1). Most of that energy, 85%, is from fossil fuels (petroleum, natural gas, and coal) (Figure 2.2), while electricity from hydropower and nuclear power is the other major component (Figure 2.3). The total for nonhydro renewable for electricity was around 6 EJ, with biomass-waste and wind the major contributors (Figure 2.4). Comparison of generation of electricity for the major consumers of energy, population, and GDP is shown in Figure 2.4, with the United States and

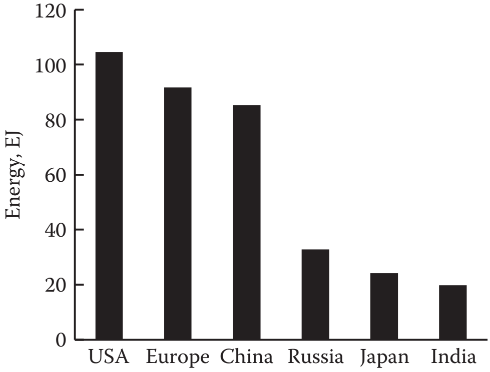

FIGURE 2.1 Consumption of energy, 2007, for nations with large population or large GDP.

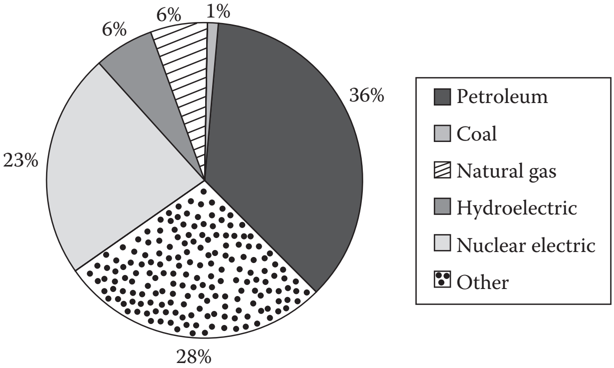

FIGURE 2.2 Consumption of world energy, 2008, by source.

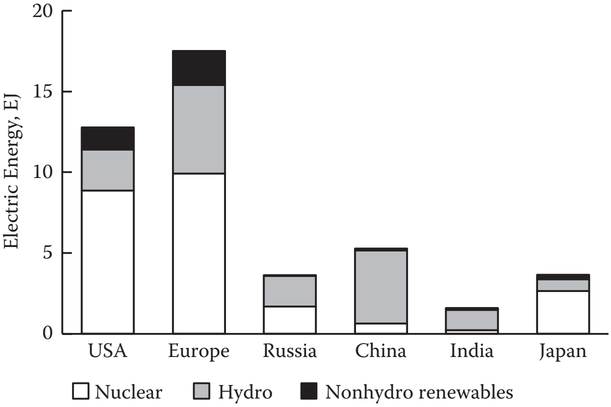

FIGURE 2.3 Electric energy from nonfossil fuels for nations with large populations or large GDP.

Europe leading in nonhydro renewables. Generation of electricity by small wind, photovoltaic, and hydro systems does not show on this scale; however the Energy Information Administration (EIA) now breaks out renewable data. Capacity and estimation of energy production for all renewable energy systems are covered in detail in subsequent chapters, and more technical aspects are covered in the series *Renewable Energy and the Environment* [4].

The United States, with 4.6% of the population of the world, consumes 22% of its energy resources and a major portion of the mineral resources; now, demand from the developing world is increasing (see Figure 1.3). The energy flow for the United States shows that fossil fuels are still the major source of energy (Figure 2.5). The energy flow for the world will be similar in that fossil fuels account for most of the energy sources; the only difference is there would be no imports. At the end-use sectors (transportation, industrial, commercial, and residential), over 50% is wasted energy. Therefore the quickest and most economic way to reduce the use of fossil fuels and emissions is to reduce consumption, primarily by the more efficient use of energy.

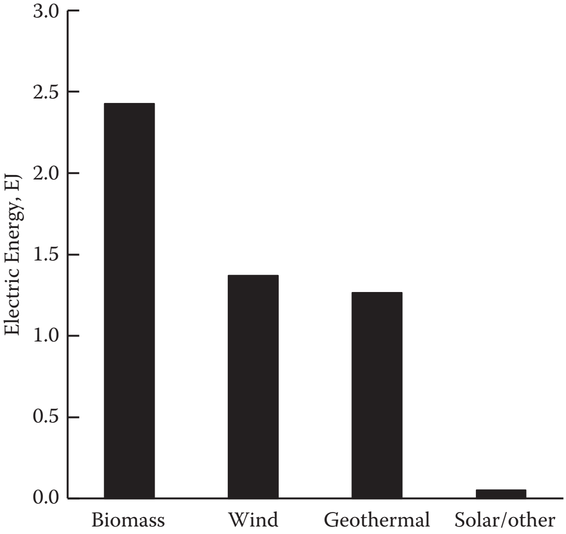

FIGURE 2.4 World electric energy from nonhydro renewables.

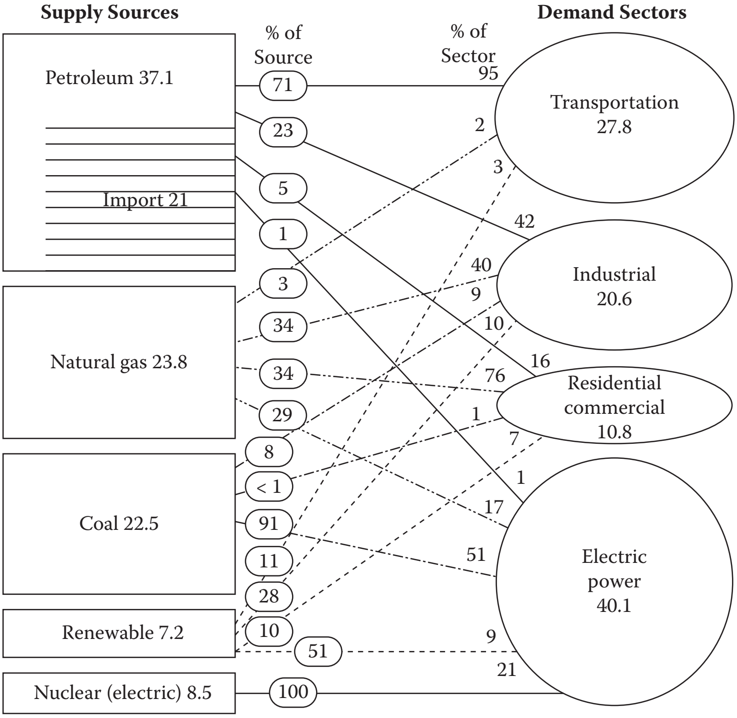

FIGURE 2.5 Energy flow for the United States, 2008, from production (%) to end-use sectors (%) plus percentage from supply sources and percentage of demand sectors. (Data from Energy Information Administration (EIA), U.S. Department of Energy. http://www.eia.doe.gov/.)

The magnitude of the problem can be seen by the cost for petroleum imports in the United States. Notice that data for crude oil production and petroleum supply/consumption are different as oil supply includes crude oil, natural gas plant liquids, and other liquids. In 1973, U.S. consumption was 6.2 Gbbl (barrels)/yr, and approximately 40% was imported, so the cost was around \$100 * 10^9 per year for imported oil at \$40/bbl (if the cost is adjusted for inflation, it would be double as oil would be \$90/bbl in 2009 dollars). Even though consumption of imported oil was reduced in the 1980s, the cost was still expensive. In the 1990s, oil consumption and imports in the United States increased again toward the previous levels, and in 2005 consumption was over 7 Gbbl/yr. Due to the world financial crisis, petroleum consumption in the United States decreased to 6.5 Gbbl in 2008, with 62% imported at \$100/bbl, for a cost around \$400 * 10^9. If domestic production continues to decrease at the past rate, future costs for imported oil will continue to rise even if the price per barrel remains the same. However, the EIA predicts a decline in imports again to the 40–50% range due to increased domestic production and increased efficiency [5].

2.6.1 OIL

The important concept is that crude estimates of resources give fairly good answers regarding when production for finite resources will peak. Also, predictions on the future use of the resource can be made from past production as production and consumption of a finite resource will probably be similar to the bell curve. In 1956, Hubbert [6] predicted that the U.S. oil production would peak in the mid-1970s, and he was close as the actual peak occurred in 1970 (Figure 2.6). The prediction (logistic curve) of U.S. oil production in Figure 2.5 used actual oil production through 2006, and the prediction was calculated in a spreadsheet using the method of Deffeyes [7, Chap. 7]. Even with the production from Alaska and offshore oil fields, total production has decreased, and imports have increased to cover that decline and the increased demand.

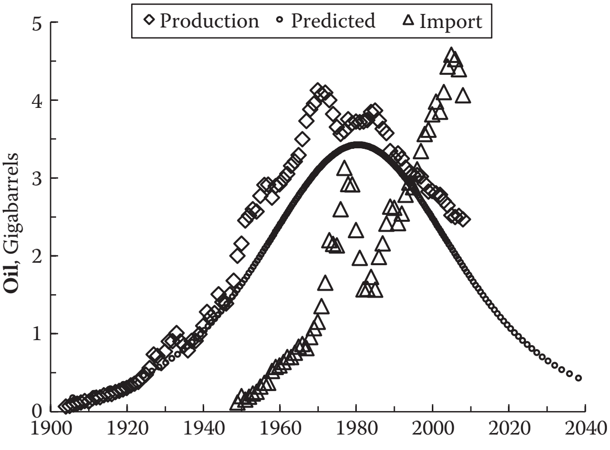

FIGURE 2.6 U.S. oil production and imports with predicted curve.

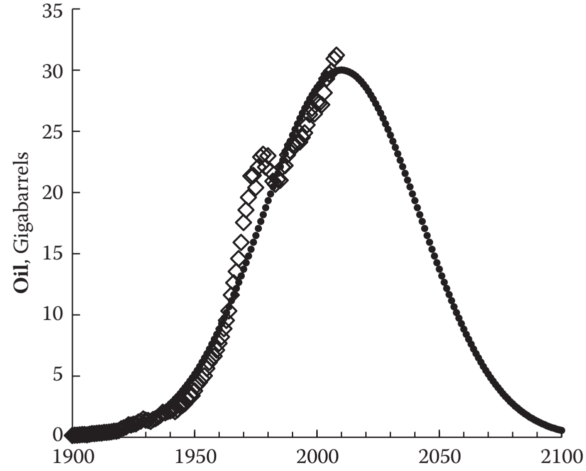

FIGURE 2.7 World oil production and predicted curve.

Even if a larger resource base is assumed, with exponential growth the larger resource is used up at about the same time. Also, as the resource is used, it becomes more difficult to obtain the resource; that is, it takes more energy and money to obtain the resource. The amount of oil and natural gas discovered per meter of hole drilled decreases exponentially. The same type of analysis and predictions can be made for natural gas, coal, and nuclear ore.

The bell curve, also called the normal or Gaussian curve, will not be exact for predicting future production as advanced technology will allow us to recover more of the fossil fuels and extend the time the resource is available. However, the end result is still the same.

World oil production [8] will follow the same pattern as oil production in the United States. Notice that the bell curve predicts world oil production (Figure 2.7) will peak around 2010. Demand decreased in the industrial nations with the world financial crisis in 2008; however, it will not change much of the analysis. There are a number of Web sites on peak oil. The oil poster (http://www.oilposter.org) is well done, and it also shows the world oil peak at 2010. Future production is stretched out because it includes heavy oil, deep-water oil, polar oil, and natural gas liquids, all of which will be more expensive. Note the cost of the BP oil leak in the Gulf of Mexico in 2010. The reaction to the oil crises of 1973 and 1980 was increased efficiency, which shows as a dip in production. However, as developing countries demand more energy, the demand and production will in general be approximated by the bell curve. In the past, the U.S. EIA predicted cheap energy ($20/bbl) for 2030, and even in 2006 they were predicting future oil at $45/bbl for 2030 for the reference case. Their long-term predictions (even the high case) are probably low as prices in 2008 were already above $100/bbl, and in 2009 with world demand reduced, prices were still at $60/bbl. Now, the EIA [5] is predicting a steady increase in the price for oil plus a modest increase in production over the next 20 years. For EIA predictions, check the forecast and analysis section on their Web site, http://www.eia.doe.gov/oiaf/forecasting.html.

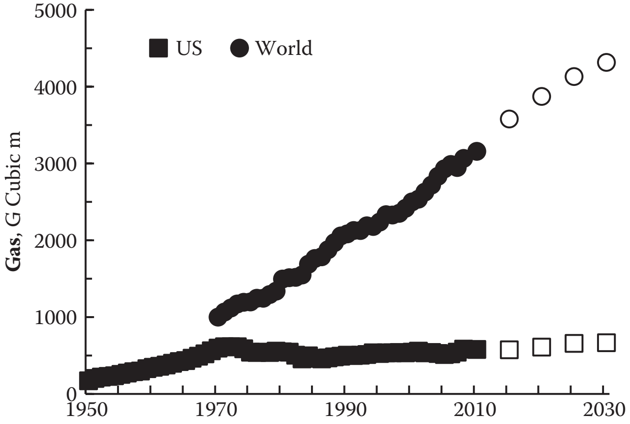

FIGURE 2.8 World and U.S. production of natural gas with predictions.

2.6.2 NATURAL GAS

Some people are touting natural gas for vehicles (compressed natural gas) because of cost for imported oil and the future decline of production of oil and because generating electricity with natural gas has less emissions; however, over the long term the problem is the same: A finite resource will be used fairly quickly [9] with increasing demand. The production of natural gas (Figure 2.8) is increasing across the world, while production in the United States has been fairly constant because of increased drilling and due to advanced technology, especially for shale formations. Production of natural gas in Russia is a bit above that in the United States, with the two countries producing 50% of world production in 1995 and 40% in 2008. Total production in the United States will be less as reserves are around 7 Tm^3 compared to Russia with 45 Tm^3. Present reserves would last around 100 yr at the 2009 rate of consumption; however, U.S. EIA predictions are for increased consumption to the year 2030 (Figure 2.8). Anyway, peak natural gas production will probably occur in the decade of 2030, although some have predicted peak production by 2020 [10]. Also, natural gas is an important feedstock for fertilizer and has been promoted as the feedstock for a future hydrogen economy, both of which would require enormous amounts of natural gas.

2.6.3 COAL

The coal industry is promoting the sustainable development of coal and conversion of coal to liquid fuels. Clean coal, which is really stretching its total environmental impact, is the promotion of coal plants that sequester carbon dioxide. Coal provided 28% of the primary energy for the world in 2008 (Figure 2.2), and over 40% of global electricity is from coal-fired plants. Production of coal has increased, especially since 2000 (Figure 2.9), because 80% of the electricity in China is provided by coal, and China is constructing new plants. Also, coal provides a major portion of heating and cooking sources in China.

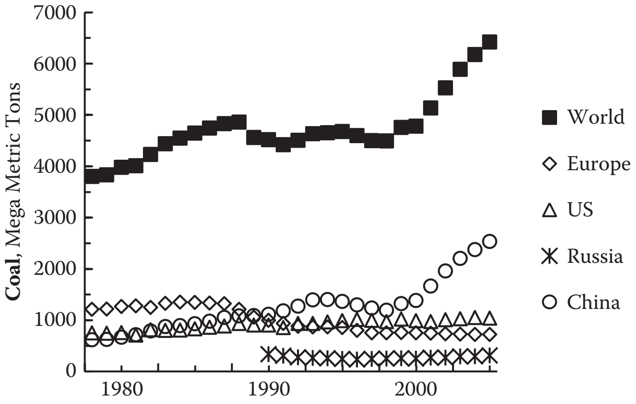

FIGURE 2.9 Production of coal in the world plus major coal-producing nations.

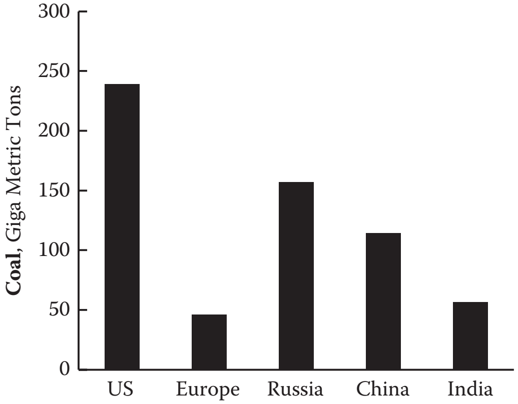

FIGURE 2.10 Major reserves of coal in the world by nation.

The United States has the largest coal reserves (Figure 2.10), and estimates are that it will last 200 years. Does that 200 years include increased production of coal as coal producers want to increase their share of the energy market? Of course, use of coal produces pollution and carbon dioxide emissions. For more information, go to the U.S. EIA Web site (http://www.eia.doe.gov/) or, for the industry viewpoint, http://www.wci-coal.com.

In the long term, the use of fossil fuels could be called the fickle finger of fate (Figure 2.11). It is obvious that the world will shift toward renewable energy with the added benefit of less environmental impact.

2.7 NUCLEAR

The first commercial nuclear plant was built in 1957, and as of 2009 [11–13] there were 436 nuclear power plants in the world, with an installed capacity of 370 GW and a production of 2,594 TWh (Figure 2.12). Five plants are in long-term shutdown,

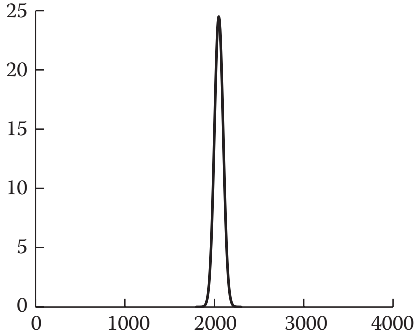

FIGURE 2.11 World use of fossil fuels on long timescale.

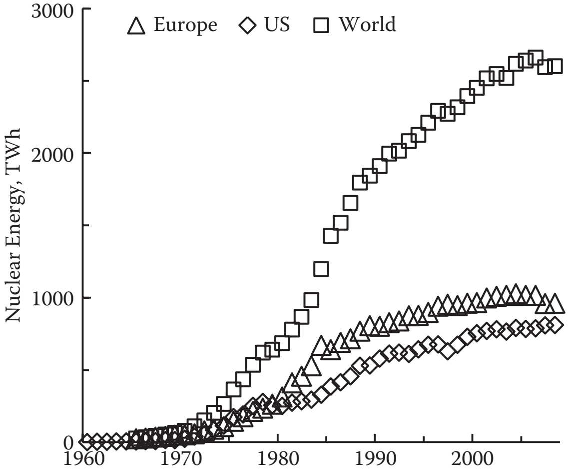

FIGURE 2.12 Production of electricity from nuclear power plants. Notice that Europe and the United States have a large portion of the total.

and 47 are under construction. They provide 14% of global electricity, with the largest percentage in France at 77% from 59 plants. The EIA is predicting the generation of 3,800 TWh for the world from nuclear power plants in 2030, around a 50% increase.

In the United States, there are 104 plants (installed capacity 106 GW, production 806 TWh); however, no new nuclear plants have been constructed in a number of years, and the percentage of U.S. electricity from nuclear power has declined from 23% to 19% as new electric plants produce electricity from natural gas and wind farms. There is a revival of interest in nuclear power in the United States, with applications for licenses, and the industry wants federal funding for construction. Nuclear power has had a large amount of funding for R&D in the United States and continues to receive substantial federal funding. Again, consult the EIA Web site for more information. An advantage of nuclear power is that there are no carbon dioxide emissions; however thermal plants still need water, and the amount of uranium ore is finite.

2.8 FINITE RESOURCE

The cumulative consumption of a resource from any initial time to any time T can be calculated by summing the consumption per year. This can be done using a spreadsheet or calculated. If the magnitude of the resource is known or estimated, then the end time T_E when the resource is used up can be estimated for growth, constant, or declining consumption using the same methods. Mathematics of resource consumption and lifetime of a finite resource are given in Appendix 1.

The cumulative consumption is the area under the curve, for example, world oil production in Figure 2.5; the estimated resource is the area under the predicted curve. Since those values were in a spreadsheet, the sums would give the total consumption to date and estimated total. Through 2008, the world had consumed 1,220 Gbbl of oil of an estimated resource of 2,400 Gbbl.

The simplest estimate for T_E is to use estimated reserve and divide that number by the present annual consumption. Of course, as supply declines, prices will increase, and demand will decrease, so the T_E will be longer.

Example 2.4

There are around 1,200 Gbbl left of the world conventional oil, and at the present rate of consumption of 31 Gbbl/yr, the lifetime is

$$T_E = 1{,}200/31 = 38 \text{ yr.}$$

If the demand is small enough or is reduced exponentially or reduced at the depletion rate, a resource can essentially last a long time. However, with increased growth, the time before the resource is used is generally short.

Example 2.5

If you do not use the equation for T_E in the Appendix, a spreadsheet is useful for calculations as you can play with different scenarios of growth and size of the resource. A growth rate of 3% per year was used. So, at around 25 years all the conventional oil is gone.

Year	Consumption	Cumulative
0	3.00E+10	
1	3.09E+10	3.09E+10
2	3.18E+10	6.27E+10
3	3.28E+10	9.55E+10
.	. . . .	. . . .
23	5.92E+10	1.00E+12
24	6.10E+10	1.06E+12
25	6.28E+10	**1.13E+12**
26	6.47E+10	1.19E+12
27	6.66E+10	1.26E+12

TABLE 2.1
Estimated Resources or Reserves, 2008

Resource	Amount
U.S. crude oil	$42 * 10^9$ barrels
U.S. oil	$80 * 10^9$ barrels
U.S. natural gas	$1.8 * 10^{12}$ m^3
U.S. coal	$243 * 10^9$ metric tons
U.S. uranium oxide	$1 * 10^5$ metric tons at $66/kg
http://www.eia.doe.gov/cneaf/nuclear/page/reserves/ures.html	$4 * 10^5$ metric tons at $110/kg
World crude oil (conventional)	$1.1 * 10^{12}$ barrels
World oil; includes heavy, sands, shale, deep sea, polar oil	$2.1 * 10^{12}$ barrels
World natural gas	$175 * 10^{12}$ m^3
World coal	$907 * 10^9$ metric tons
World uranium oxide	$2 * 10^6$ metric tons at $80/kg
http://www.euronuclear.org/info/encyclopedia/u/uranium-reserves.htm	$5 * 10^6$ metric tons at $130/kg

The example reinforces a previous statement: Exponential growth means large resources do not last long. Even with polar, deep-sea, tar sands, and oil shale, the lifetime will not be that much longer under present rates of consumption.

Similar analyses for other fossil fuels and uranium ore from estimated resources (Table 2.1) emphasize their finite lifetime under present rates of consumption. If the demand is small enough, is reduced exponentially, or is reduced at the depletion rate, a resource can essentially last a long time. However, with increased growth, T_E can be calculated for different resources, and the time before the resource is used is generally short. Remember, these are only estimates of resources, and other estimates will be higher or lower [14,15].

According to the energy companies, the continued growth in energy use in the United States is to be fueled by coal (largest fossil fuel resource), natural gas, nuclear, imported oil, and imported natural gas. How long can coal last if we continue to increase production to offset decline in production of oil and to reduce the need for importation of oil? Also, increased or even current production rates of fossil fuels will have major environmental effects as global warming has become an international political issue.

2.9 SUMMARY

Continued exponential growth is a physical impossibility in a finite (closed) system, and the Earth is a finite system. Previous calculations made about the future are just estimations, and possible solutions to our energy dilemma are as follows:

1. Conservation and more efficient use of energy. Since the first energy crisis, this has been the most cost effective mode of operation. It is much cheaper to save a barrel of oil than to discover new oil.

2. Reduce demand, transition to zero population growth, and begin a steady-state society.
3. Redefine the size of the system and colonize the planets and space; however, this will not alleviate the problem on Earth. From our present viewpoint, the resources of the solar system are infinite, and our galaxy contains over 100 trillion stars.

Because the Earth is finite for population and our use of the Earth's resources is also limited, a change to a sustainable society, which depends primarily on renewable energy, becomes imperative on a long timescale.

For the world, we will have to do the following in the transition period (next 25 years), in order of priority:

1. Implement conservation and efficiency.
2. Increase substantially the use of renewable energy.
3. Reduce dependence on oil and natural gas.
4. Use clean coal, which has to include all social costs (externalities).
5. Make use of nuclear energy.
6. Reduce environmental impact, especially greenhouse gases.
7. Implement policies (incentives and penalties) that emphasize items 1 and 2.

State and local polices must be the same. Efficiency can be improved in all the major sectors: residential, commercial, industrial, transportation, and even the primary electrical utility industry. National, state, and even local building codes would improve energy efficiency in buildings. Finally, there are a number of things that you as an individual can do about conservation and energy efficiency.

For a few final comments, the possible future for human society involves conservation and efficiency, with an orderly transition to sustainable energy and a steady state with no growth, catastrophe, or catastrophe with some revival (Figure 2.13). As overpopulation and overconsumption are affecting the Earth, an uncontrolled experiment, the most probable future for the population is catastrophe or catastrophe with some revival.

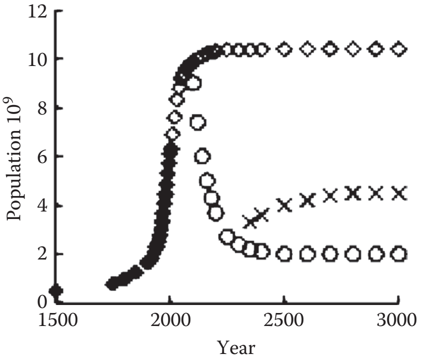

FIGURE 2.13 Population from 1500 to present with possible future populations (◇ = past, steady state; ○ = catastrophe; × = revival).

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RECOMMENDED RESOURCES

LINKS

BP Statistical review of world energy 2009. Spreadsheet historical data 1965–2008. http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622.

Earth, a graphic look at the state of the world, a great site for overview on all aspects. http://www.theglobaleducationproject.org/earth/energy-supply.php.

Energy Information Administration, U.S. Department of Energy. http://www.eia.doe.gov. The EIA site contains a lot of information on U.S. and international energy resources and production. Reports and data files can be downloaded in both PDF and spreadsheet formats.

International Atomic Energy Agency. http://www.iaea.org.

International Energy Agency. http://www.eia.org.

Peak Oil. http://www.peakoil.com.

United Nations. Information on population and projections on population. http://www.un.org/esa/population/unpop.htm.

U.S. Census. Information on world population. http://www.census.gov.

World Energy Council. Survey of energy resources 2007. http://www.worldenergy.org/documents/ser2007_final_online_version_1.pdf; http://www.worldenergy.org/publications/survey_of_energy_resources_2007/default.asp.

Worldmapper. Shows morphed countries of the world where size depends on topical data, such as population, oil exports, oil imports, and others. http://www.worldmapper.org.

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PROBLEMS

Order of magnitude (OM) problems: provide an answer of only one or two significant digits with power of ten.

1. A snowball, mass = 0.5 kg, is thrown at 10 m/s. How much kinetic energy does it possess? What happens to that energy after you are hit with that snowball?
2. For your home, estimate the power installed for lighting. Then, estimate the energy used for lighting for 1 yr.
3. From problem 2, estimate the energy saved if you converted your lighting from incandescent to compact fluorescent. Fluorescent lights are more efficient, providing more light per watt.
4. What is the maximum power (electrical) used by your residence or home (assume all your appliances, lights, etc. are on at the same time)?
5. Approximately, at your residence or home, what is your average electrical energy usage per month?
6. What is the power rating of your vehicle (convert to kW)? What is the fuel efficiency (mpg or km/L)?
7. OM: Average fuel efficiency is 24 mpg in the United States. If efficiency is raised to 35 mpg, how many barrels of imported oil per year would be saved? At $60/bbl, how much money would be saved?
8. OM: Same as problem 7 but assume fuel efficiency is 50 mpg.
9. The Hawaii Natural Energy Institute tested a 100-kW OTEC (ocean thermal energy conversion) system. The surface temperature is 30° C, and at a depth of 1 km the temperature is 10°C. Calculate the maximum theoretical efficiency for this OTEC system. Remember that you have to use degrees kelvin.
10. Go to some Web sites for ethanol and obtain their numbers for energetics of producing ethanol from corn.

11. Efficiencies of thermal power plants can be around 40%. What is the efficiency of producing electricity from fuel cells? From combined cycle gas turbines?
12. Go to a Web site for the night sky of Earth. What is the main source of light in the Middle East?
13. For the latest year that data are available, what percentage of world energy was from fossil fuels?
14. What is the estimated time for peak production of coal in China, the United States, the world?
15. OM: The Chamber of Commerce and the Board of Development are always promoting their city as the place for new industry. If a city has a population of 100,000 and a growth rate of 10% per year, what is the population after five doubling times? How many years is that?
16. OM: The world population in 1985 was around $4.5 * 10^9$ (the first time I taught the course) and after 24 years (2009), it was around $6.8 * 10^9$. How many people will there be on the Earth by the year 2050? Assume the present rate population growth as 1% per year.
17. OM: If the population growth rate could be reduced to 0.5% per year, how much longer would it take to reach the same population as in problem 16 for the year 2050?
18. OM: The most economical size of nuclear power plants is around 1,000 MW. How many nuclear power plants would have to be built in the United States over the next 50 years to meet the long-term historical growth of 7% per year in demand for electricity? In 2008, the generating capacity for the United States was around 1 million MW.
19. OM: From problem 18, what is the total cost if the installed cost of a nuclear plant is around \$3,000/kW? Suppose coal plants were installed at \$1,500/kW; what is the cost?
20. OM: Assume new electric power plants in the United States are to be fueled by coal, and the electric growth rate is 5%. U.S. generating capacity was around 1.1 million MW in 2010. How many metric tons of coal would be needed for the year 2050? Use the following conditions: Plants were operated at 95% capacity, and the efficiency of conversion is 35%.
21. OM: What is the efficiency at a nuclear power plant if the incoming steam is at 700°C and the outgoing steam is at 310°C. Remember that you have to use degrees kelvin.
22. OM: Use the coal reserves of the United States from Table 2.1. At today's rate of consumption, how long would that last?
23. OM: For problem 22, assume a coal consumption growth rate of 10% per year. How long will U.S. coal last?
24. If you could reduce your heating, cooling, and lighting bill by 50%, how much money would you save at your residence?
25. OM: Use natural gas reserves for the world from Table 2.1. At today's rate of consumption, how long would that last?
26. OM: Use uranium oxide ore reserves for the world from Table 2.1. At today's rate of consumption, how long would that last?

27. OM: For problem 27, assume a growth rate of 7% for nuclear power plants. At today's rate of consumption, how long would that last?
28. OM: The population of the world is predicted to reach $11 * 10^9$. Mexico City is one of the largest cities in the world at $2 * 10^7$ people. World population in 2009 was $6.8 * 10^9$. How many new cities the size of Mexico City will have to be built to accommodate this increase in population?
29. OM: China has embarked on a policy regarding use of cars, from thousands in 1985 to millions on the road in 2009. Suppose China acquired the same number of cars per person as the United States. How much oil would China need per year? Compare that number with present annual oil production. Would there be a problem?
30. List at least three to five ways you are going to save energy this year.

3 Sun

3.1 SOLAR POWER

The sun is a big ball of plasma composed primarily of hydrogen (92%), helium (8%), and small amounts of other atoms or elements. A plasma is where the electrons are separated from the nuclei because the temperature is so high (kinetic energy of nuclei and electrons is large). By the process of fusion, protons are converted into helium nuclei plus energy. The sun (Table 3.1) is a stable main sequence star with an estimated age of $4.5 * 10^9$ years and will continue for another 4 to $5 * 10^9$ years before starting the next phase of evolution, the burning of helium. At that point, the sun will expand and be larger than the orbit of the Earth.

Nuclei are composed of nucleons (Figure 3.1), which come in two forms: protons (which have a positive charge) and neutrons (no charge). The gravitational interaction is attractive, so in the center of the sun the protons are close enough together for the nuclear interaction to occur, even though the protons repel one another due to their charge. At the size of nuclei (10^{-15} m), the nuclear interaction is stronger than the repulsion of the electromagnetic (EM) interaction. Protons are converted into helium nuclei, and because the mass of the helium nucleus is less than the mass of the

TABLE 3.1
Characteristics of Sun and Earth

	Sun	Earth
Diameter, km	1,392,000	12,740
Mass, kg	$1.99 * 10^{30}$	$5.98 * 10^{24}$
Surface temperature, K	5,800	300

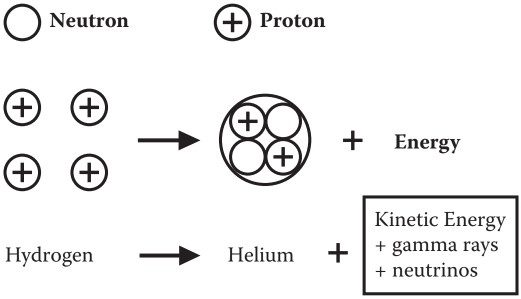


FIGURE 3.1 In the center of the sun, protons are converted into helium nuclei plus energy.

four protons, that difference in mass (around 5 * 10^9 kg/s) is converted into energy. That energy is transferred to the surface of the sun, where EM radiation and some particles (solar wind) go off into space.

This tremendous amount of energy is radiated into space from the surface of the sun with a power of 3.8 * 10^{23} kW. The Earth only intercepts a small portion of the sun's power; however, that is still a large amount. At the top of the atmosphere, the power intercepted by the Earth is 1.73 * 10^{14} kW, equivalent to 1.35 kW/m^2. Remember that this surface is perpendicular (90°) to the sun. If a surface is at an angle to the sun, the same amount of energy is spread over a larger area. At the surface of the Earth on a clear day, this solar insolation is around 1.0 to 1.2 kW/m^2 on a surface perpendicular to the sun from 9 to 15 h, depending on the amount of haze in the atmosphere and on elevation.

3.2 ELECTROMAGNETIC SPECTRUM

There are two ways of describing nature: particles and waves. Particles have mass, are localized in space, and can have charge and other properties, and no two particles can occupy the same space. Waves have no mass and are spread out over space; waves obey the principle of superposition, which means that two or more waves can occupy the same space at the same time. EM waves (Figure 3.2) travel at the speed of light and are described by their wavelength and frequency, which are related by

$$c = \lambda * f \tag{3.1}$$

where c is the speed of light, 3 * 10^8 m/s; λ is the wavelength, m, distance from peak to peak of the wave; and f is the frequency in hertz, which is the number of cycle/second (as a wave moves by a point, the number of peaks or crests per second). If you know either wavelength or frequency, you can calculate the other quantity. The speed of light will be different in a material; however, in air the speed is essentially the same as in a vacuum. EM radiation consists of oscillating electric and magnetic fields, perpendicular to each other and perpendicular to the direction

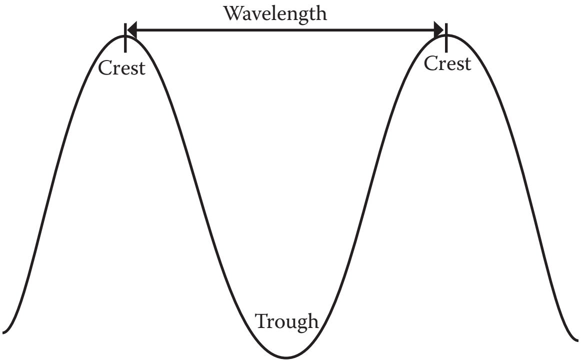


FIGURE 3.2 Wavelength is the distance from peak to peak of a wave.

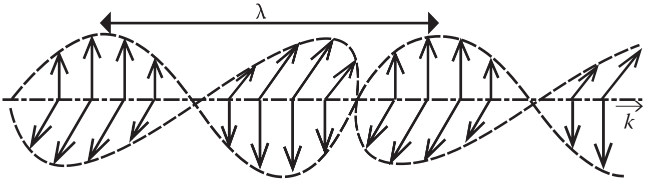


FIGURE 3.3 Diagram of electromagnetic wave showing components of electric and magnetic fields; the wave is traveling to the right.

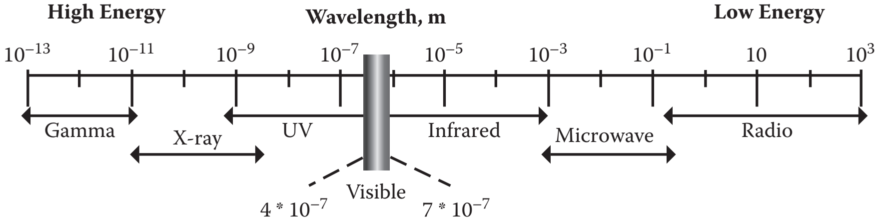


FIGURE 3.4 Electromagnetic spectrum from gamma radiation to long-wavelength radio waves.

of motion of the wave (Figure 3.3). A good applet of an EM wave is provided at http://www.walter-fendt.de/ph14e/emwave.htm.

The EM spectrum (Figure 3.4) is the range of EM radiation from very short wavelengths (large frequency) to very long wavelengths (small frequency). Sometimes, there is confusion between light, which refers to all EM waves, and the visible range (which previously was called light since we could see in this range). The subsections of the spectrum are labeled by how the radiation is produced and detected, and there is an overlap between the ranges. At the atomic level, the two ways of describing nature are combined, so EM waves come in units called photons; their energy is given by

$$E = h * f \tag{3.2}$$

where *h* is Planck's constant, $6.6 * 10^{-34}$ kg m^2/s. In physics texts, the symbol ν is used for frequency rather than *f*. Large frequency corresponds to high-energy photons, such as x-rays and gamma (γ) rays, which can go through materials that absorb visible light and can cause damage to the materials. Low-frequency EM radiation can also go through materials that absorb light (e.g., radio waves go through the walls of houses).

3.2.1 VISIBLE

The range of the spectrum that we can see, visible (sometimes referred to as light), is small, with red light ($7 * 10^{-7}$ m) having a longer wavelength than blue light ($4 * 10^{-7}$ m). A rainbow is a familiar example of the colors that we can see. White light is just a superposition (combination) of all the colors. All the different colors we can see and generate are just absorption and reflections of different parts of the visible spectrum. There are some animals that see in the ultraviolet (bees) and infrared (snakes) ranges. We now have detectors for the whole range of EM radiation. With an infrared detector, you can see people in the dark or the heat lost from a building. For images in the infrared spectrum, go to http://www.nationalinfrared.com/image_browser.php, and for images in the ultraviolet spectrum, go to http://www.pbase.com/kds315/uv_photos. For flowers in the visible and ultraviolet (what the bees see), go to http://www.naturfotograf.com/UV_flowers_ list.html#ROSACEAX.

3.2.2 Blackbody Radiation

A perfect absorber or emitter of EM radiation is a blackbody. The amount of radiation emitted per wavelength (or frequency) depends only on the temperature of the body and not on the type of material or atoms. So, a blackbody curve can be generated for a specific temperature, with the peak of the curve shifting to shorter wavelengths (larger frequency) for higher temperatures. A blue flame is hotter than an orange flame. A higher-temperature object emits more radiation at all wavelengths, so the curves are a similar shape, nested within one another (Figure 3.5). Notice that the peak of the curve for the sun is in the visible range, and it is interesting that our eyes are most sensitive to yellow-green light. The peak of the curve for the lower-temperature object is in the infrared spectrum.

3.3 ENERGY BALANCE OF THE EARTH

The energy balance of the Earth is essentially zero, except for the small amount of geothermal energy generated by radioactive decay. The Earth radiates the same amount of energy into space as the amount of EM energy absorbed from the sun (Figure 3.6). If the energy in versus energy out is not balanced, the Earth would increase in temperature and radiate more energy into space to be in balance again.

The solar energy or power (remember if you know one, you know the other for any time period) interacts with the Earth's atmosphere and surface of which the major component is water. Of the incoming radiation (100 units or 100%), clouds (31%) and the surface (3%) reflect a third, and the rest is absorbed by the atmosphere (19%) and the surface (47%).

The amount of EM radiation from the sun is primarily in the visible range, and this is absorbed and then converted primarily to thermal energy, which has a lower temperature, around 290 K, that radiates at longer wavelengths (peak at $1 * 10^{-5}$ m). The blackbody curve for Earth at 290 K would not even show on Figure 3.5a. This absorbed energy drives our weather in terms of evaporation and transportation of heat from the equator to the poles and provides the energy for wind and waves and currents in the ocean; some is absorbed and stored in plants through the process of photosynthesis. Some of the infrared radiation is emitted to space (clear skies), and the rest is absorbed in the atmosphere (Figure 3.7). Of the infrared radiation absorbed in the atmosphere, some is then reradiated into space, and the rest is reradiated back to Earth. Clear nights are cooler than cloudy nights because of nighttime radiation into space, which has a temperature of 3 K.

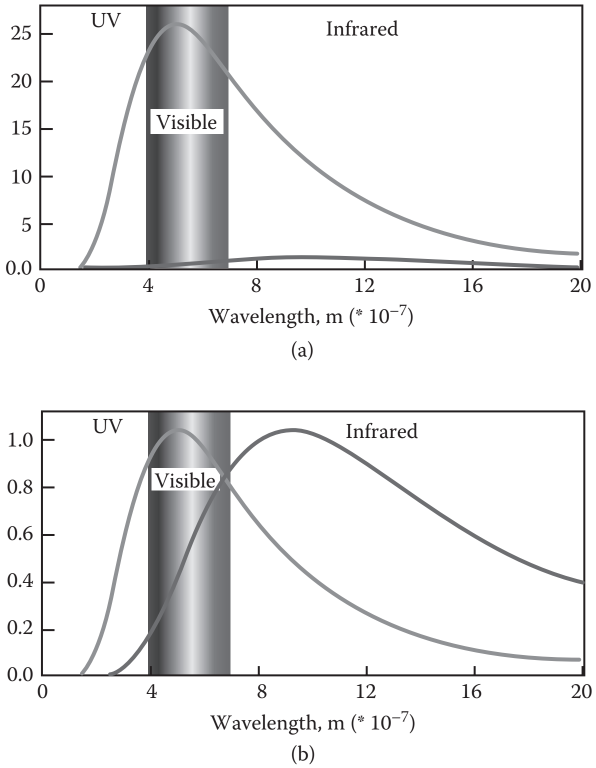


FIGURE 3.5 (a) Blackbody curve for the sun ($T = 5{,}800$ K) and a lower-temperature object ($T = 3{,}000$ K). (b) Blackbody curve for the sun ($T = 5{,}800$ K) and a lower-temperature object ($T = 3{,}000$ K). Curves now normalized to 1 to show similar shape.

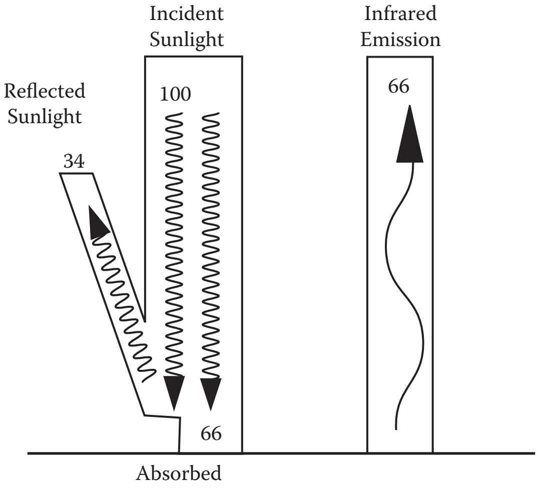


FIGURE 3.6 Energy balance of the Earth.

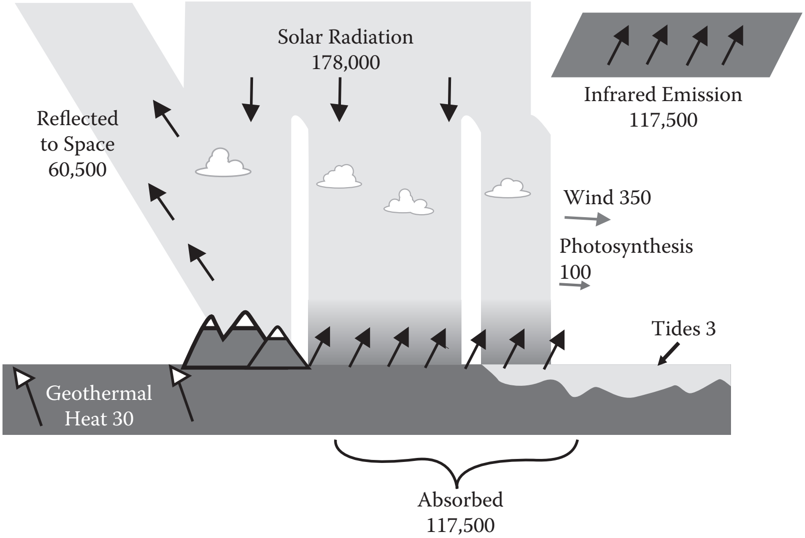


FIGURE 3.7 Transmission and absorption of electromagnetic radiation (kilowatts) and other sources of energy.

The atmosphere is transparent to visible and radio wavelengths but absorbs radiation in other wavelengths (Figure 3.8). Ozone in the upper atmosphere absorbs ultraviolet radiation. People in Australia, New Zealand, and Tierra del Fuego are now recipients of more high-energy ultraviolet radiation as we have been destroying the ozone layer at the poles in the upper atmosphere (Figure 3.9). Some of you may remember that industry maintained we could not replace the gas in refrigerators because of economics and the chemistry for ozone destruction was not completely certain. Some people who disagree with findings by scientists refer to this as junk science. Would people in supersonic planes high in the atmosphere have to worry about EM radiation? Do astronauts out in space have to worry about high-energy EM radiation?

3.4 EARTH-SUN MOTION

The inner planets are quite different because of their distance from the sun and different mass (Figure 3.10), which then determines the amount of incident energy and how much atmosphere is retained. Mercury is too close to the sun, which makes for a hot temperature, and has too small a mass to retain an atmosphere; therefore, the molecules escape into space. Venus, which was once thought to be a sister planet to Earth, is completely covered by clouds and has a dense atmosphere of carbon dioxide. Venus retains the incident energy from the sun at a higher surface temperature because the atmosphere absorbs the infrared radiation, trapping the thermal energy. Earth has liquid water and an atmosphere primarily of nitrogen and oxygen, both of which store heat and make the temperature range suitable for life. Mars is too small and too far away from the sun, so it has little atmosphere and is cold. A site for information on the solar system is http://www.solarviews.com.

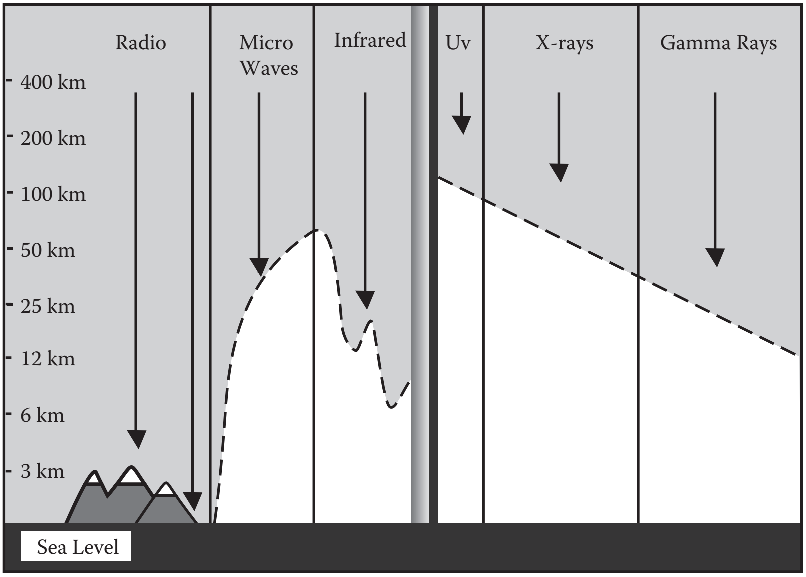


FIGURE 3.8 Visible and radio waves reach the surface, while other radiation is absorbed in the atmosphere.

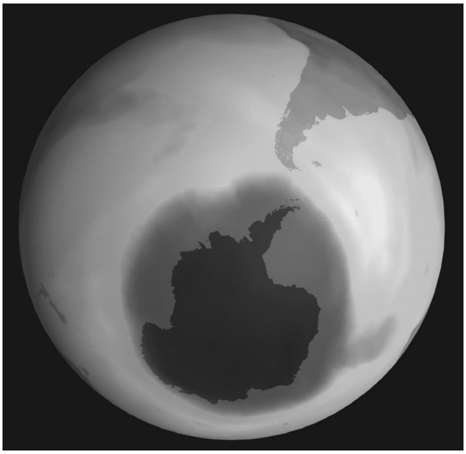
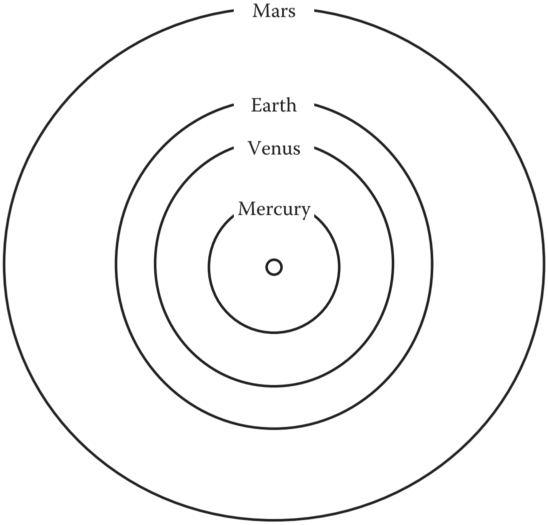


FIGURE 3.9 Large ozone hole that is three times larger than the United States over Antarctica (dark shade). Notice that the hole reaches to Tierra del Fuego in South America. (*Source*: NASA.)

3.4.1 EARTH MOTION

The Earth rotates (orbital motion) around the sun once a year in an ellipse (almost a circle) and rotates (spins) on its axis once a day. The Earth is actually closest to the sun on January 1. The orbital radius from the sun determines how much solar energy is available, and the tilt of the spin axis (23.5°) from the plane of the orbital motion



Sun Diameter 1,390,000 km

Inner	Distance from Sun		Temperature (°C)		Atmosphere
Planets	(000 km)	Mean	Max	Min	
Mercury	57,910	179	427	−173	None
Venus	108,200	482			CO_2
Earth	149,600	15	58	−89	N^2, O^2
Mars	227,490	−63	20	−140	small CO_2

FIGURE 3.10 Relative size of orbits of the inner planets plus temperature and atmosphere.

determines the seasons. The motion of the sun across sky changes during the year due to the tilt of the axis of the Earth. For example, the point where the sun rises or sets goes from 23.5° south of east-west to 23.5° north of east-west.

Winter occurs in December in the Northern Hemisphere and in June in the Southern Hemisphere because of the tilt of the axis of the Earth (Figure 3.11). The amount of solar energy per surface area depends on the angle of the surface of the Earth in relation to the sun (Figure 3.12). Notice in Figure 3.12 that the white lines on the surface are equal length, so that the same amount of energy in the Northern Hemisphere in winter is spread over a much larger area, plus the hours of daylight are shorter. The two obvious positions of the sun are height above the horizon at noon and where it rises or sets. This angle changes by 47° from June 21 to December 21. At noon, the sun is directly overhead (90°) at the equator on March 21 and September 21, and it rises and sets due east and west at the equator and other latitudes. Because sunrise and sunset are for the edge of the sun and not the center of the sun, at higher latitudes those angles are not quite due east and west.

In Figure 3.12, it is summer at the South Pole, with sunlight 24 h per day, and at the North Pole there is no sunlight. In the Northern Hemisphere, it is winter because the same amount of incident radiation is spread over a larger area, as shown by lines equal distance apart, and that amount of energy is spread over a larger area in the winter.

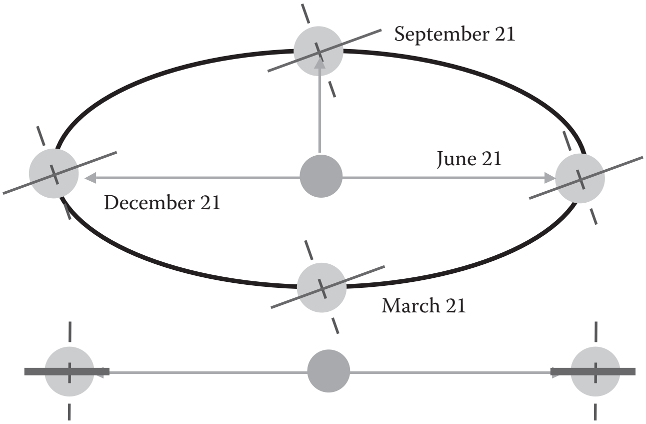


FIGURE 3.11 Seasons are due to the tilt of the axis of the Earth of 23.5° to the plane of orbit.

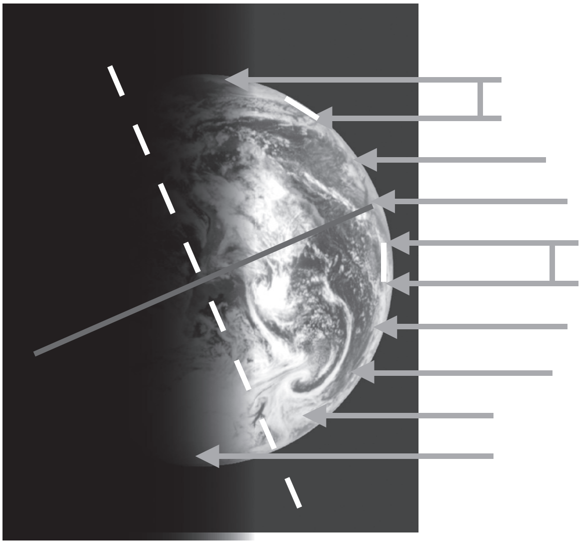


FIGURE 3.12 Effect of tilt of the axis of the Earth on incident radiation. Dark line indicates the equator, dashed white line indicates spin axis, and white lines indicate same length on surface of the Earth.

3.4.2 SUN POSITION

Location on the Earth (Figure 3.13) is measured by longitude (lines from the North to the South Pole, 0 at Greenwich, England) and latitude (north latitude and south latitude from equator) in degrees (360), minutes (60), and seconds (60). Also, for global positioning systems (GPSs) and some maps, latitude and longitude are given in units of degrees and minutes (decimal), so there are no seconds. Position or location on the Earth can be found to within 2 to 3 m with a GPS, which are now inexpensive and are in mobile phones and iPads. The 360° of longitude are divided into 24 time

FIGURE 3.13 Longitude and latitude lines. Notice the lines for 23.5° for latitude N (Tropic of Cancer) and S (Tropic of Capricorn), where the sun will be directly overhead at noon on June 21 and on December 21.

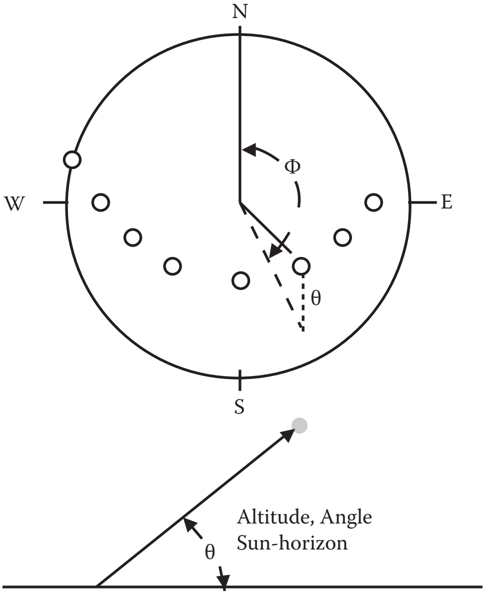


FIGURE 3.14 Position of the sun given by altitude *q* and azimuth *f*.

zones, with universal mean time (UMT) the time at longitude 0, so you need to know how many time zones you differ from UMT to determine the local time. For central time in the United States, there is 6 h difference from UMT. Also, remember that during the summer some locations have daylight savings time.

The position of the sun (Figure 3.14) can be calculated for any location and any time [1]. The position of the sun is given by two angles, altitude and azimuth. The altitude is the angle of the sun above the horizon, and azimuth is the angle from north to the projection on the Earth of the line to the sun. The position is symmetrical about solar noon (which is different from 12 noon). Previously, sun path diagrams were published for different latitudes and months and showed the sun angle. Now, Web sites are available to calculate the sun position for any location (see the Links section). In some Web sites for sun position, the direction of zero azimuth can be chosen, generally north or south.

3.5 INSOLATION

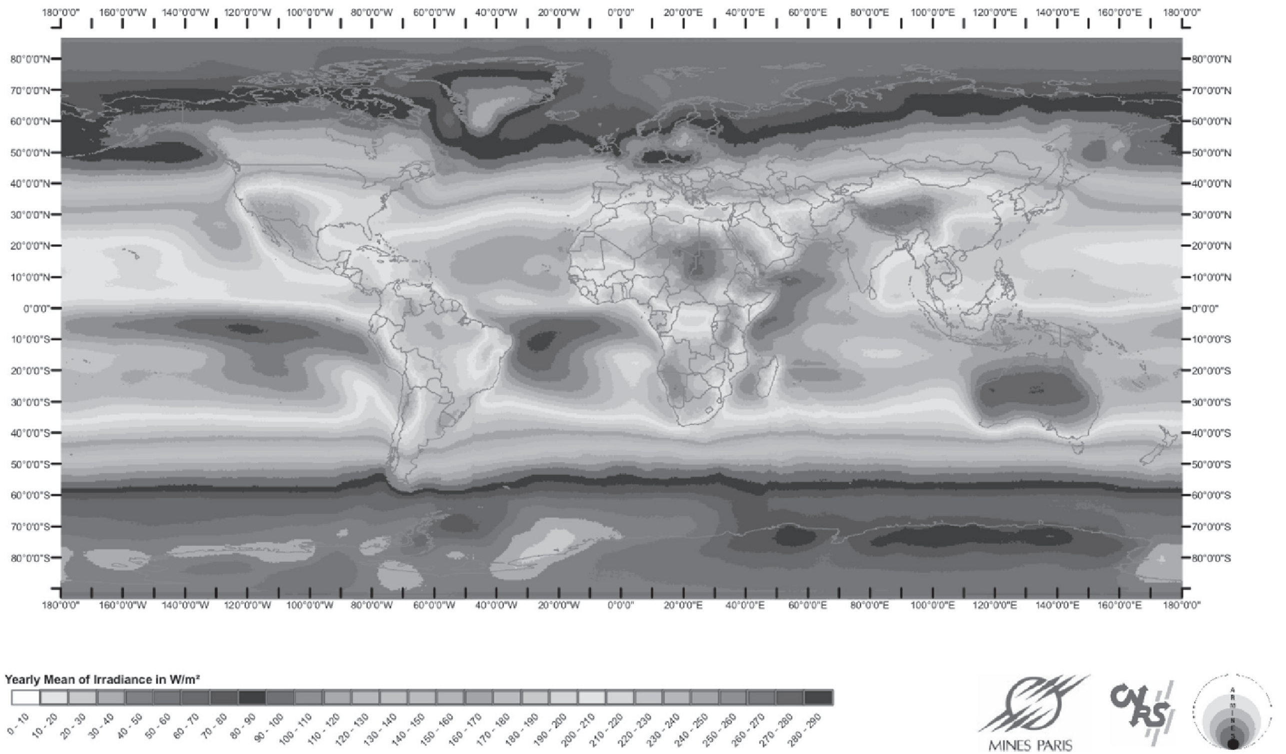
Insolation is the solar radiation at the surface of the Earth and is given in units of energy/square meter (for some time period, which is really power) or power/square meter, which is generally for an average by day, month, or year. Global insolation is composed of two components, direct and diffuse. Direct radiation is the amount of radiation on a surface perpendicular to the sun, and diffuse radiation is the indirect radiation from the sky and reflected radiation from other objects on the surface. The primary component of diffuse radiation is sunlight scattered in the atmosphere by air molecules, dust, water vapor, pollution, and the like. The predominant color on a clear day is blue, and on overcast days the sky is gray. Insolation depends on length of day, clouds, haze and pollution, and elevation above sea level.

A class 1 monitoring station measures global and diffuse radiation. Many sites just measure the total insolation for a horizontal surface. The units and time period can be different; however, generally the units used now are kilowatt hours per square meter per day or watts per square meter averaged for a time period. Previously, the units were langleys (cal/cm^2) per day. Remember, the day includes night hours when there is no solar radiation. Another way of looking at insolation is to say that the sunshine can be averaged over the day and is equivalent to the peak value for 6 h. On clear days, that insolation is around 1.0 kW/m^2.

3.6 SOLAR RESOURCE

From the measurements of solar radiation, there are solar maps (Figure 3.15) available for the world [2,3], regions, and nations (Figure 3.16) of the world and for regions or states within nations. As expected, the regions with the highest solar energy potential are the deserts on land and regions with few clouds over the oceans. Remember that elevation also is a factor. A good interactive map for the Western Hemisphere is available from 3Tier [4], which shows insolation in kilowatt hours per square meter per day. Overlays are solar, satellite, terrain, and hybrid, with tools for map size and selection, plus the additional feature of radiation type (direct normal, global horizontal, and diffuse).

Solar maps are also calculated for each day using data from satellites. These values are calculated using GOES-8, GOES-10, METEOSAT-7, and GMS-5 visible satellite images for each daylight hour. The approximate amount of energy reaching the ground is calculated for each image. This model takes into account the effect of clouds if there are clouds present. Every night, the images are integrated to give the estimated total amount of energy reaching the ground from the sun. Maps and data sets (Table 3.2) are available for average day, month, and annual (22 years of data) for the world and regions [5]. Global solar energy data for 1,105 ground sites are also available.



Realized by Michel Albuisson, Mireille Lefèvre, Lucien Wald.
Edited and produced by Thierry Ranchin. Date of production: 23 November 2006.
Centre for Energy and Processes, Ecole des Mines de Paris / Armines / CNRS.
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FIGURE 3.15 Average insolation for 1990–2004 for the world. (Courtesy of Ecole des Mines de Paris/Armines 2006.)

FIGURE 3.16 Solar map for the United States, flat plate tilted at latitude. (From National Renewable Energy Laboratory (NREL), Dynamic Maps, GIS Data and Analysis Tools, Solar Maps, http://www.nrel.gov/gis/solar.html.)

A major source of information for solar insolation for the United States is the Renewable Resource Data Center (RReDC) [6] at the National Renewable Energy Laboratory (NREL). Solar resource radiation resource maps [7] by month and for different orientations (tracking concentrator, tracking flat plate, and flat plate at different angles) (Figure 3.17) are available from NREL.

3.7 GREENHOUSE EFFECT

The atmosphere functions like a blanket, keeping the heat of the Earth from radiating into space (Figure 3.18). The atmosphere lets solar insolation in but keeps most of ground infrared radiation from going out. The greenhouse gases are water vapor, carbon dioxide, methane, and other trace gases. A large atmosphere of carbon dioxide can drastically change temperature at which the energy balance occurs, with Venus a drastic example.

The greenhouse effect is amply demonstrated on a sunny day by your car interior with the windows closed. The incident light passes through the windows and is absorbed in the material inside, which then radiates (infrared) at the corresponding temperature. The windows are opaque to infrared radiation, and the interior becomes hotter until there is again an energy balance.

TABLE 3.2
Average Insolation (kWh/m²/day) for Some Cities in Canada

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Edmonton	1.45	2.36	3.41	4.25	4.91	5.42	5.55	4.76	3.52	2.18	1.43	1.21	3.37
Victoria	1.00	1.82	2.93	4.01	5.13	5.54	5.85	5.28	3.88	2.17	1.11	0.86	3.29
Winnipeg	1.21	2.08	3.27	4.55	5.54	5.8	5,85	4.84	3.32	2.21	1.33	1.02	3.41
St. Johns	1.56	2.27	3.48	4.19	4.76	5.05	5.05	4.54	3.53	2.29	1.43	1.27	3.28
Halifax	1.56	2.31	3.46	4.09	4.82	5.27	5.41	4.86	3.92	2.54	1.53	1.3	3.42
Toronto	1.44	2.27	3.19	4.13	5.15	5.83	5.67	4.82	3.66	2.47	1.48	1.20	3.44
Montreal	1.45	2.36	3.41	4.25	4.91	5.42	5.55	4.76	3.52	2.18	1.43	1.21	3.37
Regina	1.14	1.96	3.02	4.69	5.48	5.79	6.14	4.96	3.42	2.29	1.30	0.95	3.42

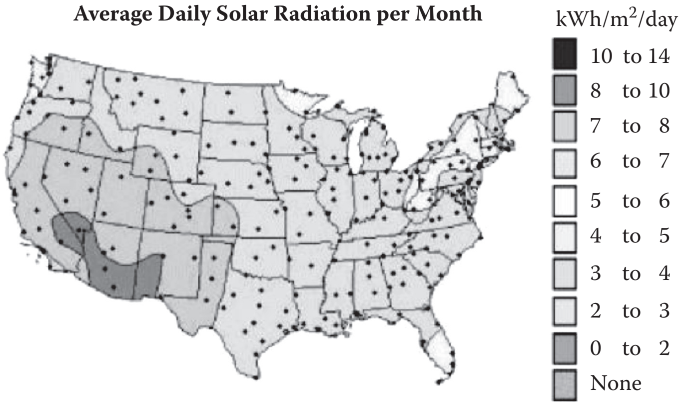

FIGURE 3.17 Solar insolation map for horizontal flat plate for the United States for June. (From National Renewable Energy Laboratory (NREL), Dynamic Maps, GIS Data and Analysis Tools, Solar Maps, http://www.nrel.gov/gis/solar.html.)

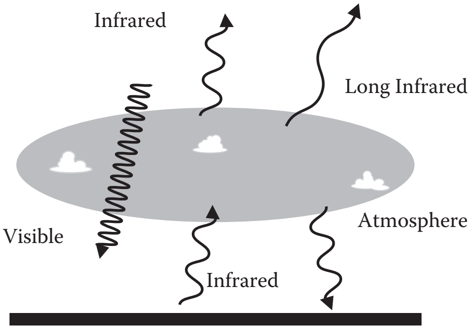

FIGURE 3.18 Greenhouse effect due to different transmission, absorption, and emission of radiation.

There is an increase in carbon dioxide in the atmosphere due to the increased use of fossil fuels, and most scientists say this results in global warming [8]. Previously, industry and many politicians said the same thing about global warming as said about the ozone problem. Industry maintained that we cannot reduce the production of CO_2 because of economics and because the science for CO_2 and global warming is not completely certain. The former U.S. policy under the G. W. Bush administration was in sharp disagreement with that of the other industrialized countries, and the reasons were that it would cost too much and not enough provisions were made to curtail future emissions from developing countries. An interesting comment by Robert Romer [9] in 1976 was that "human activities do not now have a large effect on the global climate, however this calculation should not be considered as justification for complacency." So, within 30 years we are doing an uncontrolled experiment on the atmosphere of the Earth, and now most predictions on global warming and climate change (see Links section) are for problems (even catastrophe) by 2050 to 2100 unless carbon dioxide emissions for the world are reduced to 1990 levels.

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7. Solar radiation resource maps, http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/
8. Intergovernmental Panel on Climate Change. 2008. Climate change 2007: impacts, adaptation and vulnerability. http://www.ipcc.ch/ip ccreports/ar4-wg2.htm.
9. Robert H. Romer. 1976. *Energy, an introduction to physics*. Freeman, New York.

RECOMMENDED RESOURCES

LINKS

Sun Position and Sun Path

Code available from NREL. Solar position and intensity. http://rredc.nrel.gov/solar/codes_algs/solpos/.

Sun path calculator. http://www.learn.londonmet.ac.uk/packages/daymedia/axel/sky/sunpath_calc.html.

Sustainable by design, http://www.susdesign.com; shareware, also output tables, Sol path, interactive, http://www.susdesign.com/solpath/index.php; sun position, http://www.susdesign.com/sunangle.

United States. NOAA. Solar calculators. http://www.srrb.noaa.gov/highlights/sunrise/gen.html.

University of Oregon, Solar Radiation Monitoring Lab. Sun path chart program. http://solardat.uoregon.edu/SunChartProgram.html.

University of Western Australia. The Sun's path. http://engnet.anu.edu.au/DEpeople/Andres.Cuevas/Sun/SunPath/SunPath.html.

Global Warming and Climate Change

Carbon Trust. Climate change—a business revolution. http://www.carbo ntrust.com/publications/CTC740_busin ess_rev%20v5.pdf.

Environmental Protection Agency. http://www.epa.gov/globalwarming.

Global Climate Change Impacts Report. June 2009. http://www.globa lchange.gov/publications/reports/scientific-assessments/us-impacts.

Global warming: early warning signs. http://www.climatehotmap.org.

Intergovernmental Panel on Climate Change. http://www.ipcc.ch.

National Climate Data Center, NOAA. http://www.ncdc.noaa.gov/ol/climate/globalwarming.html.

Natural Resources Defense Council. Global warming solutions. http://www.nrdc.org/globalWarming.

Union of Concerned Scientists. Global warming. http://www.ucsusa.org/global_warming.

U.S. Global Change Research Program. http://www.globalchange.gov.

Insolation Data, United States

National Renewable Energy Laboratory. Dynamic maps, GIS data and analysis tools http://www.nrel.gov/gis/solar.html.

National Solar Radiation Data Base. http://rredc.nrel.gov/solar/pubs/NSRDB/.

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T. R. Karl and K. E. Trenbrith. 1999. The human impact on climate. *Sci Am*, 281(6), 100.

Elizabeth Kolbert. 2006. *Field notes from a catastrophe, man, nature, and climate change*. Bloomsbury, New York.

Spencer R. Weart. 2008. *The discovery of global warming*. Harvard University Press, Boston.

PROBLEMS

1. Take a penny or a ring. How far away from your eye would it have to be to have the same angular size as the full moon (that is, to just block out the moon)? Note that the moon and sun have the same angular diameter because of difference in size and distance from the Earth. **Do not** try this with the sun as looking directly at the sun will damage your eyes.
2. Choose any day; go outside and estimate the angle (altitude) of the sun at solar noon (high point) and then the angle (azimuth) at sunrise or sunset. Be sure to note date and location. **Do not look directly at the sun.**
3. Choose any day; go outside and estimate for either sunrise or sunset the number of degrees from due east or due west. Be sure to note date and location (estimate latitude).
4. With the windows rolled up on your car for over an hour on a sunny day (outside temperature 15°C or higher; 15°C = 60°F), estimate the temperature inside.
5. Calculate the power of the sun. Use $E = mc^2$ and the amount of mass converted to energy per second.
6. Find the altitude and azimuth for sunrise (and the same for sunset) and solar noon for your hometown on your birthday. Use Sustainable by Design Web site (http://www.susdesign.com).
7. Find the path of the sun across the sky for June 1 and September 1 for your hometown. Use Sustainable by Design Web site (http://www.susdesign.com). What is the altitude at solar noon? What is the azimuth at sunrise and sunset?
8. OM (order of magnitude): Has the burning of fossil fuels (stored solar energy from the past) changed the energy balance of the Earth? Only use energy consumption for the world from fossil fuels for the past ten years.
9. Find an annual solar insolation map for your country. What is the insolation for your home town?

10. Go to the 3Tier Web site (http://www.3tier.com/en/) and find the annual solar insolation for Salem, Oregon, and Austin, Texas.
11. Which regions of the world have high solar insolation (Figure 3.15)? Why?
12. Estimate the average incident solar energy for a 2-m^2 flat-plate solar collector for your location. The collector is installed at an angle equal to the latitude. (a) For December; (b) for June.
13. Estimate how much more energy a gamma-ray photon has than a green (visible) photon.
14. An infrared wave has a wavelength of 0.001 m. What is the frequency? A red light has a wavelength of $7 * 10^{-7}$ m. What is the frequency?
15. Why is Venus so hot?
16. What is the range of predictions for the temperature increase for Earth by 2050? By 2100?

4 Heat Transfer and Storage

4.1 INTRODUCTION

Two primary uses for solar energy are heating and lighting for buildings. The building must be designed for the collection of solar energy, transfer of that energy, and storage. The electromagnetic radiation is absorbed and becomes thermal energy (*heat*); therefore, we need to know how heat is transferred. Heat is just internal kinetic energy of a material and is the random motion of atoms and electrons. Two important aspects for buildings using solar energy are reduction in the transfer of heat and thermal mass so there will not be large temperature variations from day to night or even over 3 to 5 days with no solar input to the building due to clouds. The reduction of heat transfer means that a solar-heated building must first be a well-insulated building, a heat trap.

Heat only flows in one direction, from hot objects to cold objects, high temperature to low temperature. *Remember that temperature and heat are not the same.* To move heat from a cold place to a hot place requires energy. For example, the air conditioner for your home uses a lot of energy. The government has promoted higher-efficiency appliances, which has saved a lot of energy. If there is no input of energy, then the heat transfer or flow is such that the objects come to the same temperature. In the winter, if there is no heat input for the building, the temperature inside will reach the outside value. In this case, the outside is so large it can be considered a reservoir, and its temperature is not affected by the small amount of heat transferred from the house. The same is true in the summer; if no heat is removed from the building, then the inside temperature will reach the outside value, and again the outside is so large that it can be considered a reservoir; its temperature is not affected by the small amount of heat transferred into the house.

Heat can be transferred by conduction, convection, and radiation. A building, especially a building designed around the climate to use solar energy, must reduce all three methods of heat transfer. You should be able to use spreadsheets to calculate the heat gain and loss. Water vapor and condensation are problems that have to be considered in buildings.

4.2 CONDUCTION

Conduction is the transfer of heat in a solid. If one side or end is at a high temperature and the other is at a low temperature, heat flows from the hot to the cold side (Figure 4.1). Conduction depends on the type of material. For example, metals are

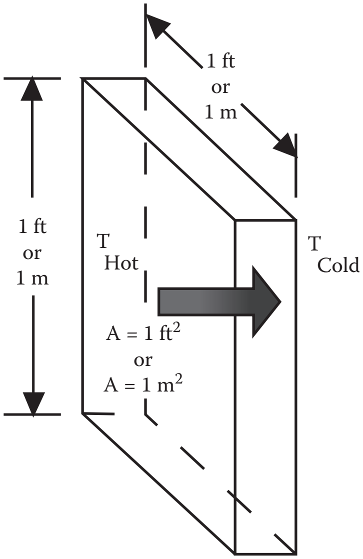


FIGURE 4.1 Conduction of heat from a hot side to a cold side.

good conductors, and polystyrene (Styrofoam) is a poor conductor of heat. The heat flow or rate (amount/time) depends on the properties of the material, thickness of the material, and the difference in temperature of the two sides. Thermal conductance is the rate of heat flow through a unit area at the installed thickness and any given delta temperature. Heat flow across slabs of material is measured experimentally and is defined in terms of thermal conductance (*U*) with units of watts per square meter per degree kelvin, W/(m^2 °K). The conversion between metric and English units is 1 W/(m^2 °K) = 0.1761 Btu/(ft^2 °F h) or 1 Btu/(ft^2 °F h) = 5.678 W/(m^2 °K).

Resistance (*R*) is a property of a material to retard the flow of heat and is the inverse of conductance. Good insulators have a high *R* value, which is low conductance. The total *R* value for a composite material is just the sum of the *R* values of the component parts.

$$U_t = 1/R_t \tag{4.1}$$

$$1/U_t = 1/U_1 + 1/U_2 + 1/U_3 + \dots + 1/U_n$$

$$R_t = R_1 + R_2 + R_3 + \dots + R_n \tag{4.2}$$

U values are measured experimentally for different materials, thicknesses, and unit area; of course, *R* values have inverse units [(m^2 °K)/W or (ft^2 °F h)/Btu]. Note that for a delta temperature, use of degree kelvin or centigrade is the same. A source for thermal conductivity values of some common materials and products is available from the Engineering Toolbox at http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.

The amount of heat loss or gain by conduction is given by

$$H_{CON} = U * A * \Delta T * h \tag{4.3}$$

where A is the area, ΔT is the temperature difference, and h is the number of hours. In the winter, you want to reduce the heat loss, and in the summer, you want to reduce the heat gain of the house.

Example 4.1

Calculate the heat transfer for a wall composed of the following materials with corresponding *R* value:

Component	***R*, (m² °K)/W**	***R*, (ft² °F h)/Btu**
Outside air film, 15-mph wind	0.03	0.17
Wood siding	0.14	0.81
Plywood sheeting, 0.5 in.	0.11	0.62
Fiberglass batt, 3 in.	2.29	13.00
Gypsum board, 0.5 in.	0.08	0.45
Inside air film	0.12	0.68
Total	2.77	15.73

From Equation 4.1, $U_t = 1/R_t = 1/2.77 = 0.36$ W/(m² °K).

The conduction heat loss for a 4.5-m² wall over an 8-h time period with the inside temperature at 21°C and the outside temperature at 5°C can be calculated from Equation 4.3.

$$H_{CON} = 0.36 \text{ (J/s)/(m}^2\ {}^\circ\text{C)} * 4.5 \text{ m}^2 * (21 - 5)\ {}^\circ\text{C} * 8 \text{ h} =$$

$$0.0112 * 4.5 * 16 * 8 * 3{,}600 \text{ W} = 746 \text{ kJ} = 707 \text{ Btu}$$

The answer has units and significant digits. Results cannot be more accurate than the one input data with least significant digits used in the calculation.

There is conduction through the framing (studs), windows, ceilings, and foundation. The wood frame (studs) of a house conducts more heat than fiberglass batts, so Example 4.1 was not correct for a wall of a house. What would be the difference if aluminum studs were used in a building? In general, there should be more insulation in the ceilings. Superinsulated houses have high *R* values for ceilings, walls, and windows (double or triple pane).

There are a number of Web sites with information on buildings and heat flow through the exterior (building envelope). The Oak Ridge National Laboratory Building Envelopes Program [1] has information on insulation and radiation barriers. The Insulation Fact Sheet has information for new (Figure 4.2) and existing houses. A map and table of recommended insulation *R* values are given for eight climate zones of the United States (Figure 4.3). A calculation for recommended insulation in

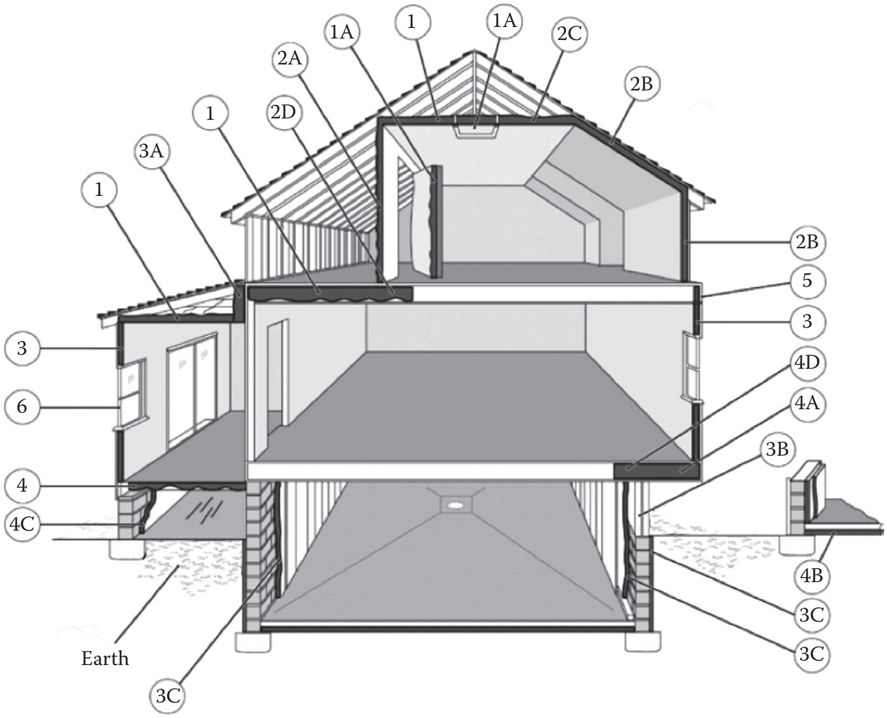


FIGURE 4.2 Locations where insulation is needed. Insulation fact sheet (insulating a new house) from Oak Ridge National Laboratory, http://www.ornl.gov/sci/roofs+walls/insulation/ins_05.html. 1. In unfinished attic spaces, insulate between and over the floor joists to seal off living spaces below.[a] 1A. Attic access door. 2. In finished attic rooms with or without dormer, insulate. 2A. Between the studs of "knee" walls. 2B. Between the studs and rafters of exterior walls and roof. 2C. Ceilings with cold spaces above. 2D. Extend insulation into joist space to reduce airflows. 3. All exterior walls, including 3A, walls between living spaces and unheated garages, shed roofs, or storage areas; 3B, foundation walls above ground level; 3C, foundation walls in heated basements, full wall, either interior or exterior.[b] 4. Floors above cold spaces, such as vented crawl spaces and unheated garages. Also insulate 4A, any portion of the floor in a room that is cantilevered beyond the exterior wall below; 4B, slab floors built directly on the ground; 4C, as an alternative to floor insulation, foundation walls of unvented crawl spaces; 4D, extend insulation into joist space to reduce airflows. 5. Band joists. 6. Replacement or storm windows and caulk and seal around all windows and doors.

[a] Well-insulated attics, crawl spaces, storage areas, and other enclosed cavities should be ventilated to prevent excess moisture buildup.

[b] For new construction, slab or grade insulation should be installed to the extent required by building codes or greater.

the United States by zip code is also available, and interactive calculators are available, one of which is for whole-wall *R* value if you know the components of the wall.

Windows have higher conductivity, so double-pane windows or storm windows will reduce conduction losses (Table 4.1). Wood frame windows have better insulation than aluminum frames; however, aluminum is cheaper. Some aluminum

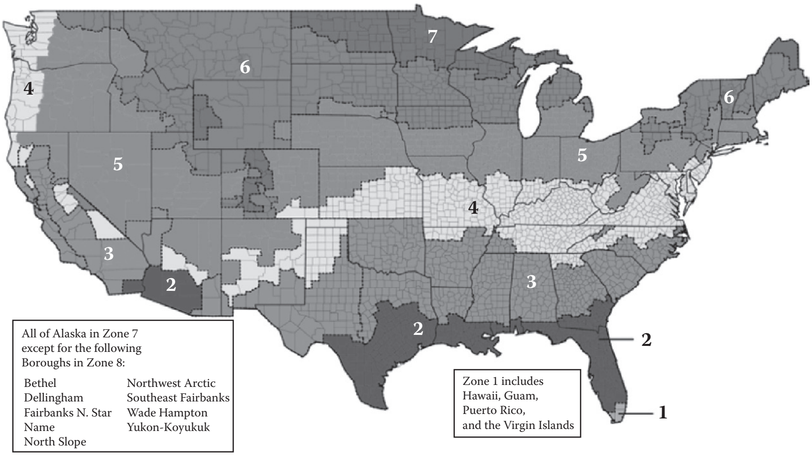


FIGURE 4.3 Insulation recommendations (*R* values) for new wood-framed houses by climate zone. Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands. Zone 7 includes most of Alaska, and Zone 8 is the northern part. (Map and table, Oak Ridge National Lab, Building Envelopes Program.)

Zone	Heat System	Attic	Cathedral Ceiling	Wall Cavity	Wall Sheathing	Floor
1	All	30–49	22–38	13–15	None	13
2	Gas, oil, heat pump	30–60	22–38	13–15	None	13
	Electric					19–25
3	Gas, oil, heat pump	30–60	22–38	13–15	None	25
	Electric				2.5–5	
4	Gas, oil, heat pump	38–60	30–38	13–15	2.5–6	25–30
	Electric				5–6	
5	Gas, oil, heat pump	38–60	30–38	13–15	2.5–6	25–30
	Electric		30–60	13–21	5–6	
6	All	49–60	30–60	13–21	5–6	25–30
7	All	49–60	30–60	13–21	5–6	25–30
8	All	49–60	30–60	13–21	5–6	25–30

windows use vinyl coverings or a thermal break to reduce conduction heat loss. Thermal shutters or shades can greatly reduce the heat loss through windows [2].

Insulation (*R* values) and thermal conductivity of building materials and air spaces (air is a good insulator) can be obtained from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2001 *Fundamentals Handbook*. Its Chapter 25, “Thermal and Water Vapor Transmission Data,” Table 4, “Typical Properties for Common Building Materials and Insulating Materials” provides thermal resistance per inch for various building materials. The handbook chapter can be purchased individually and downloaded at http://www.ashrae.org. *R* values and values for thermal conductivity for a number of different materials are available on a number of Web sites.

TABLE 4.1
***U* Values for Windows, 2.5 mm of Glass, Vinyl or Wood Frame, 2.3 cm Air Space**

No. Panes	W/(m² °K)	Btu/(ft² °F h)
Single	4.7	0.84
Double	2.8	0.50
Double, low e	1.8	0.32

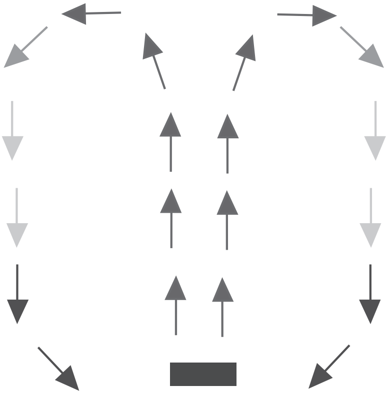


FIGURE 4.4 Convection currents from heat source.

4.3 CONVECTION

Convection is the transfer of heat by the movement of fluids—gases or liquids (Figure 4.4). Heated fluids can move by natural convection or by forced convection by pumps and fans. In natural convection or thermosiphoning, as a fluid is heated it expands and becomes less dense, thereby the hot air and the hot part of a liquid rise while the cooler part descends. So, a solar hot water system can be constructed that requires no pumps. Also, natural convection can move heat around a properly designed structure.

Convection works in conjunction with conduction. Heat from a warm or hot surface is conducted to the adjacent fluid, which is then carried away by convection. In forced convection, the quantity of heat moved depends on the amount of fluid moved (rate) and the heat capacity of the fluid. It takes a lot more air than water to move the same amount of heat.

Calculation of infiltration, convection heat loss or gain through open doors and cracks, is just an educated estimate. Even though conduction heat loss or gain through the exterior of the building is easier to calculate, reduction of infiltration (in or out through the exterior) is more important and will save energy. Infiltration barriers are now installed on the exterior of most new buildings.

$$H_{\mathrm{INF}} = c * Q * L * \Delta T * h \tag{4.4}$$

where c is the heat capacity of the fluid, Q is the volume of air leakage per length of crack per hour, L is length of crack, ΔT is the temperature difference, and h is the number of hours.

Example 4.2

A wooden, double-sash window with no weather stripping has the following values: Wind = 4.5 m/s, T inside = 22°C, T outside = 5°C, heat capacity of air = 1,297 J/(m^3 °K), Q = 1.9 m^3/(m h), L = 5 m, ΔT = 17°C, h = 8 h.

$$H_{\mathrm{INF}} = 1{,}297\ \mathrm{J/(m^3\ °K)} * 1.9\ \mathrm{m^3/(m\ h)} * 5\ \mathrm{m} * 17\mathrm{°C} * 8\ \mathrm{h} = 1{,}700\ \mathrm{kJ} = 1{,}600\ \mathrm{Btu}$$

Now, you can see why weatherization programs are cost effective. Think how much energy and money Russia could save by installing weather-tight, double-pane windows on old buildings. It would be the same as discovering a giant oil field but with the most important benefit: no depletion.

You can check for infiltration in your home on a cold, windy day by placing your hand near suspected areas, such as edges of doors and windows, electrical outlets, ceiling lights, range hoods, and a clothes dryer. You will be surprised. In the home, 70% of infiltration is around the soleplate, wall electrical outlets, exterior windows, and duct system. The soleplate is the bottom member of the wall resting on the foundation or subfloor. If you have exterior electrical outlets, the inside wall may be cool where they are located.

Dead air spaces between window panes, between window and storm window, and in walls are good insulators. The problem is the maximum width that can be used before convection reduces the R value of the space. In other words, a large-width dead air space will have convection currents.

4.4 RADIATION

Radiation was discussed in Chapter 3. Remember that all objects emit electromagnetic radiation, and the amount and wavelengths depend on the temperature. Radiation barriers, such as aluminum foil on insulation, are now well-accepted building practices. You can be in a cooler surrounding and absorb infrared (IR) radiation directly from radiant heaters to keep warm. Notice that in a fireplace the red coals emit a lot of energy (IR radiation) into the room. Do the astronauts wear aluminum underwear?

On commercial building roofs with low slopes, reflective coatings on the roof can significantly reduce energy costs. There are also reflective coatings that can be applied to the bottom side of the roof.

IR detectors can find heat leaks in structures (Figure 4.5). You can view IR photos at http://www.ir55.com/infrared_IR_camera.html and at the photo exchange of the National Renewable Energy Laboratory (NREL), http://www.nrel.gov/data/pix (do a text search for "infrared"). Notice that IR photos show leaks in the winter as hot from the outside of the house and cold from the inside.

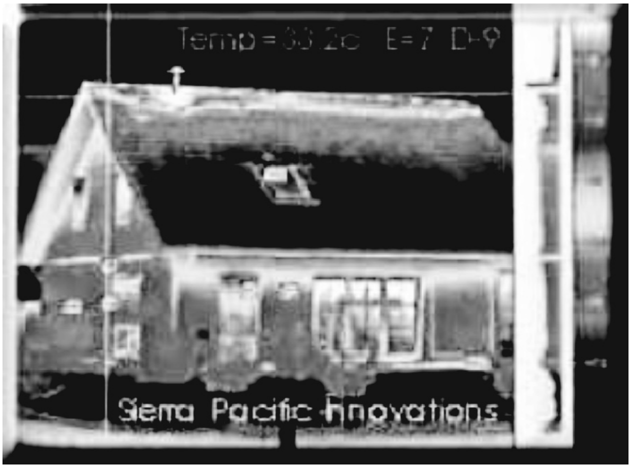


FIGURE 4.5 Infrared image for heat loss from a house. (Image, Sierra Pacific Innovations.)

4.5 THERMAL MASS

Thermal mass in solar buildings reduces temperature variations between day and night, and if there is a large mass, it can reduce temperature variations for days such that no or less auxiliary heating or cooling is required. In the summer, the thermal mass can be cooled at night, and then it absorbs heat during the day, keeping the house cool. Thermal mass is also useful in ordinary buildings as it serves as a reservoir or sink for both heating and cooling.

Thermal mass provides a means of storing the solar energy that enters through the windows. The thermal mass absorbs the solar energy during the day and keeps the house from overheating. At night, the thermal mass releases the heat, keeping the house warm. For thermal mass to be effective, air must circulate freely through the house to carry the heat from the thermal mass to the rest of the house. Natural convection will circulate the air; however, fans may be needed to assist heating in some rooms. As a general rule, more thermal mass is better. The most common materials are rock, stone, concrete, and water. In general, the heavier (in weight) a material is, the more thermal mass is available. Remember that in cold climates water can freeze and present problems in terms of breaking containers. Solutions to keep water from freezing are antifreeze or containers placed in an area where temperatures will never be below freezing. Also, water is corrosive, so ordinary barrels with water may be a problem after some time period. Finally, using water for storage presents a problem if the storage area is above ground level as a stronger structure is needed to support the weight.

4.5.1 THERMAL MASS PATTERNS

There are a number of methods or patterns for estimating the amount of thermal mass per window area and for location of the thermal mass. The rules of thumb for sizing thermal mass for passive solar homes are summarized in five patterns [3]:

Floor or wall in direct sunlight
Floor, wall, or ceiling in indirect sunlight
Floor, wall, or ceiling remote from sunlight
Mass wall (Trombe wall) or water wall in direct sunlight
Partial mass wall or water wall (containers) in direct sunlight

Then, the following interrelated factors determine the sizing characteristics:

Area of windows exposed to the sun
Mass surface area
Mass thickness
Mass material type

4.5.2 SPECIFIC HEAT

The amount of heat a material can store is determined by its specific heat, a property measured experimentally (Table 4.2). Specific heat is the amount of energy (J) needed to raise 1 kg a degree centigrade or the amount of energy (Btu) needed to raise 1 lb a degree Fahrenheit. In fact, that was how the British thermal unit was defined, and the calorie is the amount of heat needed to raise 1 g of water 1°C. The amount of heat (thermal energy) stored in a given amount of material for a temperature difference is given by

$$T_{HE} = S * m * \Delta T \tag{4.5}$$

where S is the specific heat, m is the mass, and ΔT is the temperature difference.

TABLE 4.2
Specific Heat and Heat Capacities of Common Materials

Material	Specific Heat, kJ/(kg °K)	Specific Heat, Btu/(lb °F)	Density, lb/ft³	Heat Capacity, Btu/(ft³ °F)
Water	4.2	1.00	62.5	62.5
Air	1.0	0.24	0.075	0.018
Concrete	0.9	0.22	144	34.0
Brick[a]	0.9	0.22	123	24.6
Gypsum	1.1	0.26	78	20.3
Limestone	0.9	0.22	103	22.4
Wood	2.4	0.57	47	26.8
Rock	1.2	0.28		
Soil (dirt)	0.8	0.19		

Note: For specific heat and heat capacity of some common solids (kJ/kg °K) see the Engineering Toolbox, http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html.

[a] If magnesium is added to the brick, the heat capacity is larger.

Example 4.3

For heat stored in rocks, m = 500 kg of rock, S = 840 J/(kg °C), T final = 50°C, T initial = 40°C.

$$H_{TE} = 840 \text{ J/(kg °K)} * 500 \text{ kg} * 10 \text{ K} = 4.2 * 10^6 \text{ J}$$

This is the same amount of heat given up as mass cools from 50 to 40°C.

If the heat is stored in a liquid, then the quantity is probably given in terms of volume, so you need to know the density to calculate the mass or know the heat capacity of the liquid, energy/(volume * degree).

$$\rho = m/V \tag{4.6}$$

where ρ is the density, and V is the volume.

Example 4.4

For heat stored in 4 m^3 of water, S = 4.19 kJ/(kg °C), T final = 26°C, T initial = 18°C. 1 m^3 water = 1,000 kg, so m = 4,000 kg.

$$H_{TE} = 4.19 \text{ kJ/(kg °C)} * 4{,}000 \text{ kg} * 8\text{°C} = 1.3 * 10^5 \text{ J} = 1.3 * 10^8 \text{ J} = 1.2 * 10^5 \text{ Btu}$$

4.6 SEASONAL HEATING OR COOLING

Once the U values of all exterior surfaces (envelope) have been calculated, the conduction heat loss is calculated using Equation 4.1 for each surface and then summed to estimate the total conduction heat loss. An important quantity is the hourly heat loss of the house at the outside temperature close to the lowest expected value, the design temperature. Design temperatures are listed for a number of U.S. cities. For example, the design temperature for Amarillo, Texas, is 8°F. A heating system needs to be able to deliver this amount of heat per hour during the coldest days. In general, building contractors use rules of thumb to size the heating system for the size and type of house, amount of insulation, and the design temperature of the area. Can the size of the heating system be reduced with solar heating and thermal mass?

The conduction heat loss for a heating season or months within the season is estimated using degree-days. The standard practice is to use 65°F for the inside temperature because most buildings do not require heat until the outdoor air temperature falls between 60 and 65°F. A degree-day is then the difference between 65°F and the average temperature for the day. For example, if the average outside temperature is 50°F for 7 days, then the number of degree-days is 105. See the Links section for data for heating and cooling degree-days.

Example 4.5

Calculate the heat loss for a season for a wall for Amarillo, Texas.

$$U_t = 0.064 \text{ Btu/(ft}^2\ {}^\circ\text{F h), area} = 50 \text{ ft}^2\text{, season degree-days} = 3{,}985$$

$$\text{Season degree-hours} = 3{,}985^\circ\text{F day} * 24 \text{ h/day} = 95{,}640^\circ\text{F h}$$

$$H_{\text{CON}} = 0.064 \text{ Btu/(ft}^2\ {}^\circ\text{F h)} * 50 \text{ ft}^2 * 95{,}640^\circ\text{F h} = 3.1 * 10^5 \text{ Btu} = 3.3 * 10^8 \text{ J}$$

Generally, the calculation is done by month because the heat loss will be highest in December and January.

A similar estimation can be made for season cooling, which also uses 65°F as the base. Conduction heat gain can be calculated for the hottest day of the summer to estimate the design size of the cooling system. A conduction heat gain for a cooling season is estimated by the same procedure. Again, building contractors use rules of thumb for sizing cooling systems.

4.7 THERMAL COMFORT

As you well know, thermal comfort is subjective and differs from person to person. In the tropics, when the temperature dips to 30°C (86°F), most people feel cold. We want our houses to be comfortable with a feeling of heat in the winter and a feeling of cooling in the summer. We set the thermostat at 25°C (77°F) or lower in the summer and at 23°C (73°F) or higher in winter.

Thermal comfort depends on environmental and physiological factors:
Environmental: air temperature (dry bulb), relative humidity, air speed, and radiation (mean radiant temperature, MRT)
Physiological: metabolic rate and amount of clothing (insulation)

If you are active in the winter, then you feel comfortable at lower temperatures. Previously, we dressed for winter with long underwear, sweaters, and so on, but now we expect to wear summer clothes inside buildings during the winter.

The environmental factors are interrelated in our perception of thermal comfort. Air temperature affects the amount of heat lost or gained due to convection and affects evaporation of sweat.

Mean radiant temperature affects our perception of temperature because hot and cold objects emit or absorb radiant energy, which activates the same sensory organs as heat transferred by conduction or convection. The net exchange of radiant energy between two objects is proportional to their temperature difference multiplied by their ability to emit and absorb heat. MRT is the area-weighted mean temperature of all surrounding objects, which is positive when surrounding objects are warmer than the skin and negative when they are colder. People are highly responsive to changes in MRT as the human skin has extraordinarily high absorptivity and emissivity (0.99).

This is why people have their thermostats set lower in summer than in the winter. In my office at the university, even though the thermostat is at the same level in the winter, on really cold days, I am cold because I am radiating heat to a brick outside wall and not getting radiation in return. The Efficient Windows Collaborative has information on the benefits of efficient windows and how they can reduce the radiation to enhance thermal comfort (http://www.efficientwindows.org).

Relative humidity is the amount of moisture vapor in a specific volume of air. For any dry-bulb temperature, there is only a certain amount of moisture vapor that can be absorbed in the air before it becomes saturated and precipitation occurs. Relative humidity affects the evaporation, and in hot, dry climates sweat is readily evaporated. At relative humidity above 80%, sweat is produced, but most of it cannot evaporate as the air immediately surrounding the body becomes saturated. Humidity less than 20% can dry out mucous membranes and greatly increase susceptibility to infection. In the winter, humidity in buildings may need to be increased for thermal comfort. In hot, humid climates, the control of humidity is a major factor in cooling.

Air speed is also an important factor in thermal comfort. Stagnant air in artificially heated spaces often contributes to a feeling of stuffiness, and any air movement in cold environments is often considered draughty. We can stand higher air temperatures in the summer if there is air movement; therefore, ceiling fans are now installed in many houses and other buildings. If the air temperature is less than skin temperature, air movement increases convective losses substantially. In 30–85% humidity, air movement increases the evaporation of sweat; however, air speed makes only minimal differences for relative humidity below 30%. In winter, we can stand lower temperatures if there is no air movement, so the wind chill index is a combination of air temperature and wind speed as it affects people. For example, the wind chill index is –18°C when $T = 30°\text{C}$ and the wind speed is 10 m/s.

A psychrometric chart (Figure 4.6) is used to determine the thermal comfort zone using local climatic data. That comfort zone can be enlarged (Figure 4.7) by changing air speed, humidity, and evaporative cooling in dry climates and of course by air conditioning (changing temperature).

Thermal comfort is highly subjective as is it depends not only on personal preference and acclimatization but also internal and external temperature sensing is integrated such that the overall sensation may be pleasing or displeasing depending on whether the overall effect is toward or away from the restoration of deep body temperature. A cold sensation will be pleasing when the body is overheated but unpleasant when the core is already cold. At the same time, the temperature of the skin is by no means uniform. The wearing of clothes also has a marked effect on the level and distribution of skin temperature. For the purposes of building design, comfort will be defined as the absence of thermal stress on people.

REFERENCES

1. Building Envelopes Program, Oak Ridge National Laboratory. http://www.ornl.gov/sci/roofs+walls/index.html.
2. William A. Shurcliff. 1980. *Thermal shutters and shades*. Brick House, Amherst, NH.

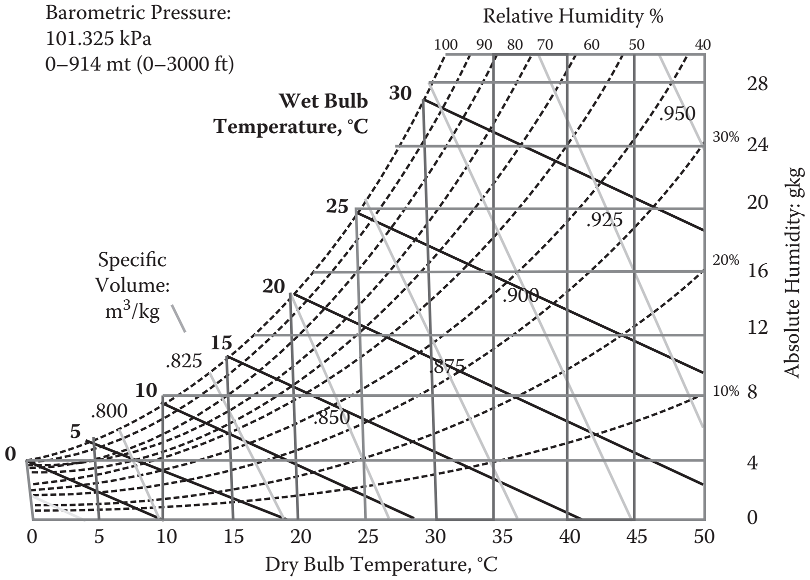


FIGURE 4.6 Psychrometric chart. (Graph from Engineering Toolbox.)

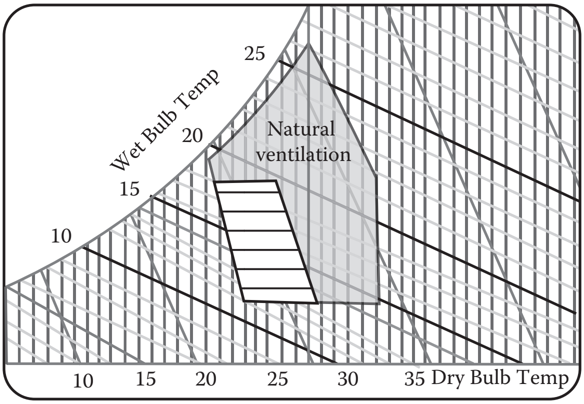


FIGURE 4.7 Thermal comfort zone (gray area) is enlarged by natural ventilation (big area). (Graph from Engineering Toolbox.)

3. *The thermal mass pattern book, guidelines for sizing heat storage in passive solar homes.* 1980. Total Environmental Action, Harrisville, NH.

RECOMMENDED RESOURCES

LINKS

Energy Efficiency and Renewable Energy, Buildings Technologies Program. Information resources. http://www1.eere.energy.gov/buildings/information_resources.html.

The Engineering Toolbox. Resources, tools, and basic information for engineering and design of technical applications. Great site for information. http://www.engineeringtoolbox.com/metabolism-activity-d_116.html.

CLIMATE DATA

National Oceanic and Atmospheric Administration, National Climatic Center. http://www.noaa.gov/climate.html.

World Climate. http://www.worldclimate.com.

HEATING AND COOLING DEGREE DAYS

BizEE. Calculates degree-day (heating and cooling) data for the world by day, week, month, or average. Results downloaded as a spreadsheet. http://www.degreedays.net/.

The Engineering Toolbox. Design conditions in U.S. states and cities summer and winter. http://www.engineeringtoolbox.com/us-outdoor-design-temperature-humidity-d_296.html.

Environmental Change Institute. Data for United Kingdom. http://www.eci.ox.ac.uk/research/energy/degreedays.php#degreedays.

National Climatic Data Center, NOAA. Heating and cooling degree data. http://lwf.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html.

National Weather Service. Degree-day monitoring and data. http://www.cpc.ncep.noaa.gov/products/monitoring_and_data/DD_monitoring_and_data.shtml.

Sustainable by Design. U.S. climate data. http://susdesign.com/usa_climate/index.php.

THERMAL COMFORT

Canadian Centre for Occupational Health and Safety. Thermal comfort for office work. http://www.ccohs.ca/oshanswers/phys_agents/thermal_comfort.html.

Efficient Windows Collaborative. http://www.efficientwindows.org.

Health and Safety Executive. Thermal comfort. http://www.hse.gov.uk/temperature/thermal/index.htm.

INNOVA, AirTech Instruments. Thermal comfort. http://www.lumasense.dk/Booklets.60.0.html.

Thermal comfort. http://personal.cityu.edu.hk/~bsapplec/thermal.htm.

PROBLEMS

1. Place your hand close (do not touch) to an incandescent lightbulb. What do you feel? How did that energy get from the lightbulb to your hand? Do the same thing with a fluorescent lightbulb that emits around the same amount of light. What is the difference?
2. When there is significant temperature difference between outside and inside the house, place your hand on a window (inside and then go outside). Note the date and inside and outside temperatures. Does the window feel hotter or colder for each situation compared to the inside and outside temperatures?
3. Place a wooden pencil and a spoon in a cup of hot water. Feel both after a short time and then after a longer time period. Their thermal conductivity differs quite a bit. Write down your observations. What if there is a metal casing on the pencil for the eraser? How does that feel compared to the wood?

4. Calculate the season heating loss for a single-pane picture window 1.2 m high by 3 m long. Use heating degree-days for Amarillo, Texas.
5. Calculate the season heating loss for a double-pane, low-e glass picture window 1.2 m high by 3 m long. Use heating degree-days for Amarillo, Texas.
6. Calculate the season cooling need for a single-pane picture window 1.2 m high by 3 m long. Use cooling degree-days for Amarillo, Texas. In other words, your air conditioner needs to remove this amount of heat from your house.
7. Calculate the season cooling need for a double-pane, low-e glass picture window 1.2 m high by 3 m long. Use cooling degree-days for Amarillo, Texas. In other words, your air conditioner needs to remove this amount of heat from your house.
8. Calculate the season heating loss for the south-facing windows of your house. Use heating degree-days for the city closest to you for which data are available.
9. Calculate the season cooling need for the south-facing windows of your house. Use heating degree-days for the city closest to you for which data are available.
10. Calculate the conduction heat loss for the following wall, 4 m long, 2.5 m tall. Calculate for 8 hr, inside temperature at 20°C and the outside temperature at –5°C. Wall components from outside to inside are: brick; 2 cm Styrofoam board; 1.2 cm plywood; wood studs, 5 × 10 cm, on 50 cm centers with open air space; 1.2 cm gypsum board.
11. Calculate the conduction heat loss for the following wall: 15 ft long, 8 ft tall. Calculate for 8 hr, inside temperature at 78°F and the outside temperature at 3°F. Wall components from outside to inside are brick; 1.2-cm (1/2-in.) plywood; wood studs, 5 × 10 cm (2 × 4), 45-cm (18-in.) centers with 9-cm (3.5-in.) fiberglass batt between the studs; 1.2-cm (1/2-in.) gypsum board. Remember that the air film adds to the insulation.
12. Estimate the infiltration loss at your home on a windy day (24 h). The outside temperature is at freezing. This will be a rough estimate. When doors are opened, they let in or out a lot of air.
13. Use Figure 4.2. When should insulation be placed for foundations?
14. Use Figure 4.3. What is the recommended *R* value for a wall cavity for a new wood frame house in your hometown? Include the town and state in your answer.
15. Use Figure 4.3. What is the recommended *R* value for the attic for a new wood frame house in your hometown? Include the town and state in your answer.
16. Calculate the heat stored in a concrete floor (10 cm thick, 3.5 m × 4.5 m), initial temperature 60°F, final temperature 80°F.
17. Calculate the heat stored in water (fifty 1-gal jugs), initial temperature 15°C, final temperature 27°C.
18. What is the design heating temperature for your home? Use the city closest to you for which there are data. Use your parents' home if needed.
19. What is the design cooling temperature for your home? Use the city closest to you for which there are data. Use your parents' home if needed.
20. At what temperature do you set your thermostat in summer? In winter?
21. Most ceiling fans will run in both directions. Why?

5 Solar Heating and Cooling

5.1 BUILDING

Heat is transferred by conduction, convection, and radiation, and the ratio of heat loss by the three modes can vary widely depending on amount of insulation, number and types of windows, radiation barrier, and infiltration. Air infiltration through open windows, doors, and vents and through cracks in the envelope of the house or around windows and doors can account for 20% to 55% of the heat loss. Even the damper in the fireplace must be closed when it is not in use.

In general, older homes have large *U* values due to single-pane windows and little insulation. Because many older homes are horrible in terms of heat loss or gain, the first step is always insulation and reducing infiltration. Weatherization programs for low-income groups are more economical than money for assistance in paying bills when energy costs are high. And, weatherization continues to save energy for a long period of time. The primary aspects of weatherization are addition of storm windows, caulking cracks, and adding insulation, especially for the ceiling.

Superinsulated houses [1] have R-40 insulation in the ceilings, 15-cm or more stud walls with R-22 batts, and 5 to 10 cm of Styrofoam insulation on the foundation. All windows would be double or triple pane in very cold climates.

For new houses, states are now implementing building codes for residences that emphasize energy conservation (reduction of heat transfer). The other aspects promoted are energy efficiency in appliances, lighting, furnaces, and air conditioning.

5.1.1 AIR QUALITY

The reduction of infiltration can mean less fresh air. Houses with less than 0.5 air changes per hour can have excessive levels of carbon dioxide, moisture, other air pollutants, and even radon from soils and groundwater in some areas. In superinsulated houses, an air-to-air heat exchanger may be necessary as the heat exchangers remove the heat from the exhaust air and transfer it to fresh intake air.

5.1.2 AIR AND VAPOR BARRIERS

The activities of the family can produce 2–3 gal of water vapor per day, and the teenager who takes a 20-min shower adds to that total. Most of the moisture is carried by infiltration. Water vapor migrates or diffuses from areas of greater to lower vapor pressure, which can be prevented with a vapor barrier. Vapor barriers are large, thin sheets of transparent polyethylene around the inside of the building envelope that limit the movement of moisture.

During the winter, moisture in the warm air can condense in wall and ceiling cavities where it meets a cold surface. If enough vapor condenses, it can saturate the insulation, reducing its *R* value, and may eventually cause rot and decay in wood materials. The following guidelines will help control condensation:

- Use materials in the outer skin that are five times as permeable as the inner skin.
- Seal all cracks and joints.
- The air barrier should be as tight as possible.

The insulation outside the vapor barrier should be twice as much as inside. In high-moisture areas, the vapor barrier should be on the warm side of the insulation.

Condensation on double-pane windows may indicate that you have problems with inadequate vapor barriers.

Air barriers are high-density polyethylene fiber films placed around the outside of the house to reduce infiltration. Air barriers allow moisture vapor to pass. If a vapor barrier is sealed carefully, it can also serve as an air barrier.

5.1.3 WIND AND VEGETATION

Wind can drastically change the heat loss or gain for a house. The conduction heat losses through the surfaces of a house increase with wind speed, as the *R* value of the air film is reduced from 0.68 to 0.17 in a 7-m/s wind. This reduction is most important for windows and doors. In addition, winds increase air infiltration through any crack or opening, and it is easily detected inside the house in cold weather just by feeling around doors and windows.

An evergreen belt of trees sheltering the house from prevailing winter winds can reduce heat loss by as much as 30%. The trees should eventually reach the height of the house, and the distance from the house should be less than five times the building height. Deciduous trees on the east and west can reduce heat gain in the summer by as much as 25%. The local agricultural extension service can recommend trees and shrubs suited to your climate. In addition, vegetation produces oxygen and absorbs carbon dioxide.

Baffles and shutters can also reduce heat transfer due to wind. Entrances should not be on the side of the house in prevailing winter winds. Windows should be also be kept to a minimum on the north due to winter winds and kept to a minimum on the west due to afternoon heating in the summer, unless the windows are shaded.

Information on wind speed and direction (wind rose diagrams) can be obtained from local, regional, or national weather service agencies. Local terrain will affect both wind speed and direction, so if you are new to an area, check with residents who have been in the area for some time.

5.2 PASSIVE

In a passive system, the solar collector and storage are an integral part of the house, and there is no auxiliary assistance for the transfer of heat within the house. You can have both passive heating and cooling; however, heating is the most common. *The most significant factors are the size and placement of windows and the sizing of the thermal mass.* Other factors are orientation, color, and shape of the house; color inside the house; plus vegetation for shading and wind control. The materials of the house act as the thermal mass; however, for conventional homes there is not enough mass for a passive system. So, for a retrofit or remodeling for passive solar, mass will have to be added.

5.3 WINDOWS AND GLAZING

Fenestration is the openings in the house, which refer to windows, skylights, and doors. In general, we think of windows as having glass panes; however, there can be other materials, so the covering that transmits the solar energy is called glazing. Remember that solar radiation is composed of the direct and diffuse (radiation from the sky and reflection from other bodies, respectively). What you want is to let the direct sunlight in the house in the winter and to shade that direct sunlight in the summer. You want the diffuse sunlight for daylighting in both winter and summer.

The incoming solar electromagnetic (EM) radiation is composed primarily of three ranges, infrared from 25 to 7.6 * 10^{-7} m, visible (sometimes also referred to as light) from 7.6 to 4.0 * 10^{-7} m, and ultraviolet (UV) from 4.0 to 3.0 * 10^{-7} m. The characteristics of the glazing are given by the division of the incoming EM radiation into the following: transmission, reflection, absorption, and the solar heat gain coefficient (SHGC). The absorbed component is reradiated in the infrared range, so in reality the incoming EM radiation is composed of transmitted and reflected radiation (Figure 5.1). The transmittance depends on the angle of incidence, being fairly constant from normal to 50° and then decreases as more EM radiation is reflected (Table 5.1). So, vertical windows, when the sun is high in the sky, transmit less direct sunlight due to less area perpendicular to the sun (cosine factor) and more reflection. However, the best strategy is to shade south-facing (north-facing in the Southern Hemisphere)

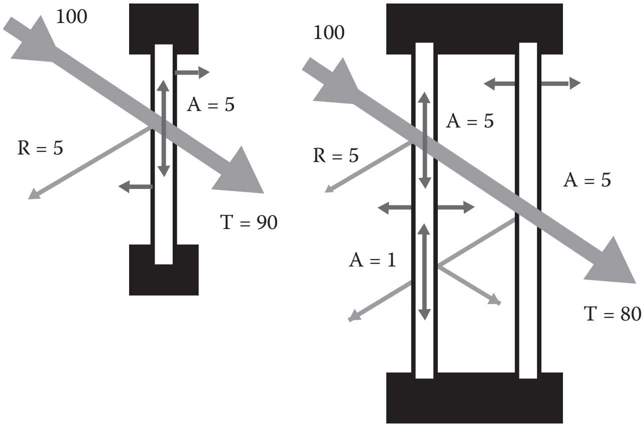


FIGURE 5.1 Incoming solar radiation for single- and double-pane windows. The absorbed radiation will not be equal for inside and outside due to the temperature differences.

TABLE 5.1
Transmittance of Glass versus Angle of Incidence

Angle of Incidence	Single Glaze	Double Glaze
0	0.90	0.81
20	0.90	0.81
40	0.89	0.80
60	0.82	0.71
70	0.77	0.59
80	0.44	0.29
90	0.00	0.00

TABLE 5.2
Transmittance of Different Glass Glazings

Glazing	Solar, %	Visible, %	*R*, (m² °K)/W	*R*, (ft² °F h)/Btu
Single clear	90	80	0.15	0.87
Double				
Clear	80	65	0.36	2.04
Coated/tinted				
Clear low e	52	74	0.55	3.13
Green “Solex”	41	68	0.36	2.04
Bronze tinted	41	48	0.36	2.04
Reflective				
Gray	6	8	0.40	2.27
Gold	9	18	0.52	2.94
Silver-gray	23	29	0.38	2.17
Silver-blue	12	18	0.40	2.27
Triple				
Clear	62	75	0.45	2.56
Clear low e	48	70	1.2	7.0

windows in summer so that no direct sunlight enters the house. Also, west windows let in too much sunlight (solar energy) in the summer during late afternoon.

Since the glazing has lower *R* values than insulated walls, you do not want all the walls of your house to be glass, although some houses with almost all glass have been built. Also, a structure with a glass envelope would overheat in the summer as too much solar radiation would be admitted. Therefore, large buildings with glass envelopes have highly reflective glass (Table 5.2) to reduce direct sunlight. There was a case when a skyscraper with reflective glass increased the heat load significantly for an older adjacent building.

Low-emissivity (low-e) glass has a thin film on the inside of the third surface to reduce the transmission of the long-wavelength infrared radiation. This reduces heat loss in the winter from inside the house to the colder space outside and reduces some of the heat gain in the summer as it blocks the infrared portion of the solar radiation. Remember that the *U* value for windows includes everything, frame and glazing. For solar heating, you want a glazing that has high solar heat gain. The reason to go to double pane is lower *U* (higher *R*) values since the dead air (or even noble gas) increases the insulation value. The following is a good site for diagrams for glass glazings with *U* values, transmission, and solar heat gain: http://www.efficientwindows.org/gtypes.cfm.

5.3.1 OTHER GLAZINGS

Fiberglass-reinforced plastics, polycarbonate (Lexan) and polyvinyl chlorides (PVCs) are available for windows, passive solar systems, daylighting, greenhouses, and so on. They can be obtained in single sheets or as component systems of two sheets plus insulation for higher *R* values. Previous disadvantages were weathering and coloring with age due to UV radiation. Sun-Lite has a Tedlar film on the exterior surface to reduce UV damage.

Material	Transmission (depends on thickness)
Sun-Lite	80–90%
Lexan	64–84%

5.3.2 SOLAR HEATING

The amount of solar energy (insolation) that comes into a building through the windows (size, orientation, glazing, and shading) depends on time of year, location, and percentage sunshine (clouds and haze). The solar heating can be estimated from tables of clear-day insolation by latitude and percentage sunshine by month (Figure 5.2 and Table 5.3). Average insolation values by month that take into account cloud cover for different angles of surfaces are available on the Internet. The data for vertical insolation indicate that in most locations vertical windows on the south can be net heat gainers, depending on climate and *R* value of the windows. Surprisingly, even single-pane windows on the south can be net energy gainers in temperate climates. Also, during the summer vertical windows let in less solar

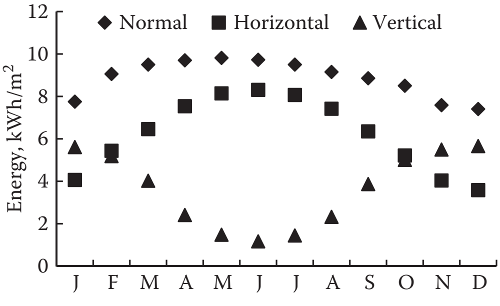


FIGURE 5.2 Clear-day insolation, average for month, for latitude 32° N.

TABLE 5.3
Clear-Day Insolation (kWh/m^2) for 32° N and Estimated Percentage Sunshine by Month for Amarillo, Texas, Area

Month	Normal	Horizontal	Vertical	% Sun
Jan	7.8	4.1	5.6	70
Feb	9.1	5.4	5.2	70
Mar	9.5	6.5	4.0	70
Apr	9.7	7.5	2.4	70
May	9.8	8.1	1.5	70
Jun	9.7	8.3	1.2	80
Jul	9.5	8.1	1.4	80
Aug	9.2	7.4	2.3	80
Sep	8.9	6.4	3.9	75
Oct	8.5	5.2	5.0	75
Nov	7.6	4.0	5.5	75
Dec	7.4	3.6	5.7	70

Note: Insolation is for 21st day of month.

energy due to the angle of the sun (cosine factor). There is more reflection due to the larger angle of incidence.

Example 5.1

Calculate the amount of solar heat that comes through a south-facing window (single pane) for January (70% sunshine).

Vertical window, 1.2 by 2.5 m, single pane, transmission = 90%

Area = 3 m^2, insolation for January is 6 kWh/m^2 per clear day

Energy hitting window per day = 3 m^2 * 6 kWh/m^2 = 18 kWh/day

Energy transmitted = 0.9 * 18 kWh/day = 16 kWh/day = 55,000 Btu/day

Energy for month = 16 kWh/day * 31 days * 0.70 = 350 kWh = 1.2 * 10^6 Btu

Maps of solar insolation for the United States by month are available from the National Renewable Energy Laboratory (NREL) for different types of collectors and orientation (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/). The two-axis concentrating collector gives the normal to the sun. The maps also take into account the percentage sunshine (Table 5.4), so the average values of energy per day do not have to be adjusted.

TABLE 5.4
Average-Day Solar Insolation (kWh/m²) for Amarillo, Texas, from NREL Solar Maps

Month	Normal	Horizontal	Vertical
Jan	6.5	2.5	4.5
Feb	6.5	3.5	3.5
Mar	7.5	4.5	3.5
Apr	9.0	6.5	3.5
May	9.0	6.5	2.5
Jun	9.0	7.5	2.5
Jul	9.0	6.5	2.5
Aug	9.0	6.5	2.5
Sep	7.5	5.5	3.5
Oct	7.5	4.5	4.5
Nov	6.5	3.5	4.5
Dec	5.5	2.5	4.5

Example 5.2

Calculate the amount of solar heat that comes through a south-facing window (double pane) for January for Amarillo, Texas.

Vertical window, 1.5 by 2 m, area = 3 m^2, double pane, transmission = 80%

Average insolation for January for vertical window is 4.5 kWh/m^2 per day (takes into account cloudy weather).

Energy hitting window per day = 4.5 kWh/m^2 * 3 m^2 = 13.5 kWh/day

Energy transmitted per month = 0.80 * 13.5 kWh/day * 31 days = 335 kWh

The double-pane window will transmit less solar heat into the house; however, it will reduce the heat loss. Therefore, in colder climates double-pane windows are better.

During the winter, vertical windows on the south (Northern Hemisphere) capture most of the solar energy available (Figure 5.3) because of the position of the sun. On December 21 (35° N, 102° W), there are 9 h of sunshine with around 6 h for solar heating (Figure 5.3). At 0900 and 1500, the altitude is 15° with azimuths of 120° and 217°, respectively. The maximum elevation is 32°, so during that 6 h, the vertical windows let in most of the sunlight. On July 21, sunrise is at 0549 and sunset at 1958. That means there are 14 h of sunshine, with the sun due east at 0900 and due west at 1650. There are 4 h when the elevation angle is above 60°, so more solar radiation is reflected by the window. However, it is still better to have the south-facing windows shaded during the summer months. The sun path across the sky can be plotted for any latitude and longitude for any day (see Chapter 3).

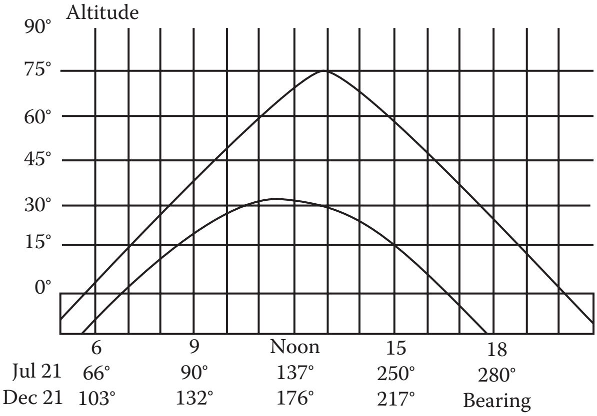


FIGURE 5.3 Path of sun for December 21 and July 21, location 35° N, 102° W. Solar noon occurs at different times primarily because of daylight savings time.

5.3.3 SHADING

The south-facing windows need to let sunlight in during the heating season and be shaded during the cooling season so that little direct sunlight enters the house. The simplest shading devices are exterior to the house, such as overhangs and awnings. Deciduous trees that provide shade on the east and west sides of the house are also effective. Even though the sun is highest and the longest day is on June 21, shading needs to be provided through August (Figure 5.4). There can be a problem with awnings as they require manual control, and if you live in a windy area they tend to get torn.

South-facing windows transmit more energy during the winter than the summer due to the solar position of the sun, even though there are more hours of sunshine during the summer. The primary factor is the angle, such that less area is perpendicular to the sun, and the other factor is that there is more reflection for angles above 60°.

Sites are available for determining the sun angle for shading for buildings. VRSolar, University of Southern California, is a Web site for teaching site solar access (http://www.usc.edu/dept/architecture/mbs/tools/vrsolar/index.html).

For the Southern Hemisphere, the sun angles are symmetric, so shading needs to be on the north. For the tropics, the days are all about the same, 12 h of sunshine. However, now you need shading for windows on both the south and north sides of the house.

FIGURE 5.4 Overhang gives shade in summer and permits direct solar radiation into the structure in winter.

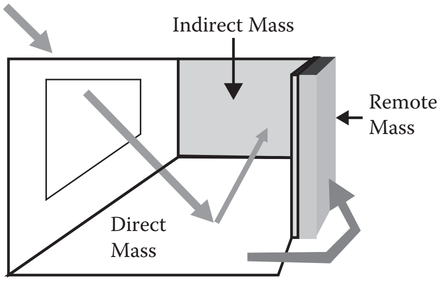


FIGURE 5.5 Direct gain with solar heat stored in direct mass (direct sunlight), indirect mass (reflected sunlight), or remote mass through convection.

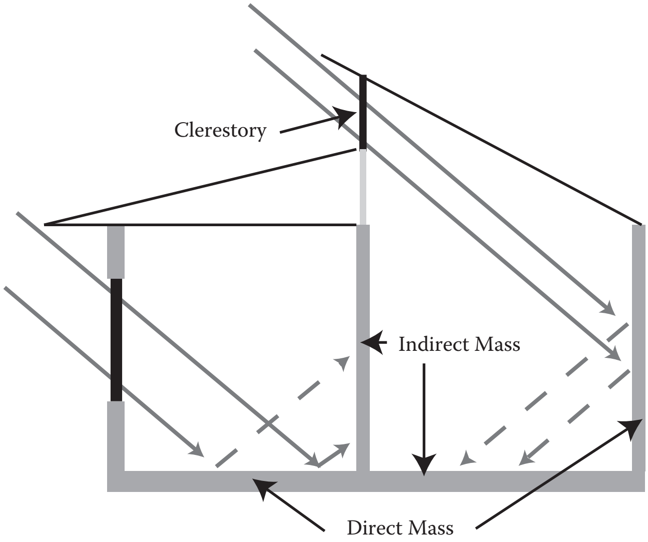


FIGURE 5.6 Direct gain through south-facing windows and clerestory. Clerestory gives direct gain into rooms that are not on the south side of the house. Overhangs shade windows in the summer.

5.4 PASSIVE HEATING AND COOLING

5.4.1 Direct Gain

Direct gain occurs when the sunlight comes through windows, skylights, or clerestories (glazings can be glass or plastic) and is absorbed in the room (Figures 5.5 and 5.6). In general, larger-area skylights are needed for solar heating; however, they are heat gainers in the summer since the sun is more directly overhead. One solution to reduce heat gain for skylights would be to install movable shades. Clerestories are a way of getting direct solar energy into rooms that are not on the south. As noted, there has to be enough thermal mass to reduce the temperature variations between sunny days and cold nights in the winter. Thermal mass also helps for passive cooling.

FIGURE 5.7 Attached greenhouse at Amarillo Children's Home that was constructed by volunteers at AEI workshop.

5.4.2 INDIRECT GAIN

Indirect gain occurs when the sunlight is absorbed and then transferred to the rest of the house by natural or forced convection, conduction, and radiation. Examples of indirect gain occur in a sunroom (solarium), attached greenhouse, Trombe wall, water wall, and solar pond. If you live in areas with freezing temperatures, then water storage may be a problem.

Attached greenhouses (Figure 5.7), sunrooms, and solariums present a way to increase space and provide heating. Many are additions to an existing house; however, some sunrooms are an integral part of the house.

Sunrooms and attached greenhouses can overheat, even in winter, so heat has to be transferred to the rest of the house or enough thermal mass needs to be available to reduce temperature variations. They may need auxiliary power for fans to circulate air to the rest of the house. Also, sunrooms and attached greenhouses need ventilation during the summer, especially if there is glazing on the roof. This can be accomplished through windows that open or ventilation fans. A patio on the north side of the house (location 35° N, 102° W), open screen on sides with a fiberglass roof, was too hot during the summer. If the primary use is for plants, then you may need auxiliary heating in the winter, especially in cold climates. Thermal shades or blankets are one possibility for reducing heat loss at night for sunrooms and attached greenhouses. Again, thermal mass will reduce the temperature variations.

Sunrooms, solariums, attached greenhouses, and large skylights from kits to design are available from a number of manufacturers. Photos of different types, layouts, and prices are available.

A Trombe wall consists of a masonry wall 20 to 40 cm (8 to 16 in.) thick coated with a dark, heat-absorbing material and covered with a single or double layer of glazing (Figure 5.8). The glazing is around 5 cm from the masonry wall, so the hot air will rise and go into the room during the day. Most of the solar energy is absorbed by the dark surface, stored in the wall, and conducted through the masonry such

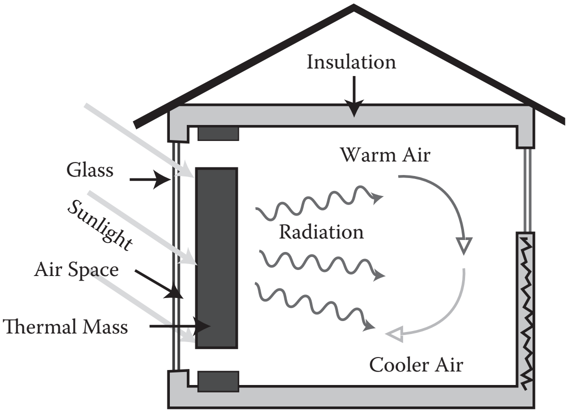


FIGURE 5.8 Indirect gain, Trombe wall.

that peak temperatures on the inner surface of the room occur later in the day (heat travels through the concrete wall about 1 in./h). For a 20-cm thick Trombe wall, the heat takes about 8 h to reach the interior of the building. This means that rooms remain comfortable through the day and receive slow, even heating after the sun sets. Rooms heated by a Trombe wall often feel more comfortable than those heated by forced-air furnaces because of warm surface radiates infrared radiation, even with lower air temperatures in the room.

If the wall is too thick, the heat takes too long to reach the room, plus there is more cost for the concrete. If the wall is too thin, it gets too hot, and the heat reaches the room from the wall during the day when you also have heating from convection. Dampers must be placed on the openings, so there is no reverse thermosiphoning at night.

The surface of the wall is painted with a flat black paint for absorption. Applying a selective surface to a Trombe wall improves its performance by reducing the amount of infrared energy radiated back through the glazing. A selective surface absorbs almost all the radiation in the visible range and emits little in the infrared range. A selective surface on a sheet of metal foil is glued to the outside surface of the wall.

Windows for direct gain and daylighting can be combined with a Trombe wall, which absorbs and stores heat for evening use. Overhangs for the Trombe wall prevent the wall from getting too hot during the summer. A Trombe wall provides most of the heating for the Zion National Park Visitor Center building (Figure 5.9). Winter surface temperatures on the inside of the Trombe wall can often reach 38°C (100°F).

Since water has a higher heat capacity than masonry, water walls can be used. These can be tubes, barrels, or even milk jugs. There are two considerations for barrels, freezing and rusting; both can result in leaks, but antifreeze and anti-corrosion substances can be used for these problems. Steve Baer (Zomeworks) built a home that had indirect gain, which consisted of insulated cover, glazing, and then barrels, which were painted black. The insulated cover, which was moved manually, was on the ground during the day with a sheet of aluminum foil to reflect more sunlight onto the barrels.

FIGURE 5.9 Visitor center has windows and clerestory for direct gain and daylighting and Trombe wall for indirect gain. The Trombe wall is the lower two rows of glass. That glazing is a single-covering, high-transmittance, patterned glass. Notice that the windows can open for ventilation. (National Renewable Energy Laboratory (NREL), http://www.nrel.gov/learning/re_solar_hot_water.html.)

Harold Hay designed a house (Skytherm) in California that had a water pond on the roof with a sliding insulating cover. The water bags absorbed heat during the day and then the heat conducted through the concrete roof and radiated into the house at night. The system worked in reverse during the summer, with the pond covered during the day and uncovered at night. It cooled at night due to radiation to the night sky. This system was not duplicated on any scale for the following reasons: weight on the roof requiring a stronger structure, manual control of insulated cover, primary suitability for mild climates with no freezing, and condensation on the concrete during the summer. An additional problem in California could be the seismic response to earthquakes.

5.4.3 Cooling

Passive cooling is the use of natural ventilation to replace hot air with cooler air by convection. At higher elevations, most nights are cool, so if you have thermal mass for passive solar heating, you cool off that mass at night, close the space during the day, and then the cooler thermal mass absorbs the heat from the air, slowing increases in temperature. Thermal chimneys are another way of getting rid of excess heat in hotter climates, as hot air in the upper part of the structure is replaced by cooler air from the outside. Soffit vents with ridgeline vents can keep attics from excessive temperatures. Low windows on the south and high windows on the north, both of which can be opened, can also create convective currents to get rid of the warmer air.

5.5 ACTIVE HEATING

In most active systems, the system (collector, storage) is separate from the building, so the system can be added to existing structures. An active heating system

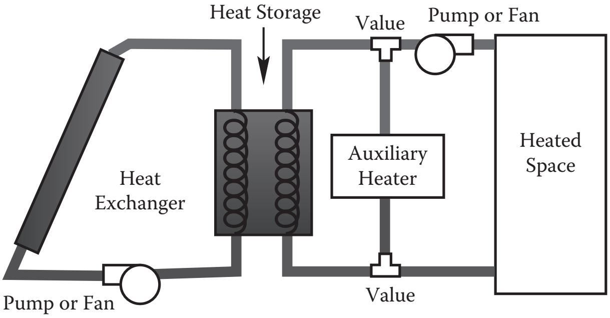


FIGURE 5.10 Active solar heating system. Notice that solar collector loop is closed so it can have antifreeze or other fluid for freezing climates.

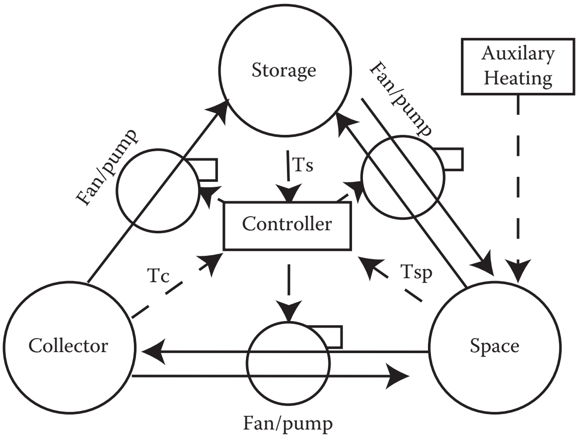


FIGURE 5.11 Diagram of an active solar heating system.

(Figure 5.10) requires power for pumps or fans for moving the fluid (air, water, or even silicone) and power for the controller for turning on pumps, valves, and so on. The main components of the system are the collector, storage, and the controller (Figure 5.11). The components of the system are as follows:

Collector: insulated box, glazing (one or more), absorber
Heat transfer: air, liquid, other
Controls
Storage
Distribution: pumps, valves, fans, dampers
Controller (thermostat): sensors for temperatures to turn distribution on and off
Auxiliary heat: may be tied into present heating system or may be two distribution systems

With a solar hot water system, the space heating can be provided by radiant water heaters or by air heating, similar to a furnace, where the air passes over a heat

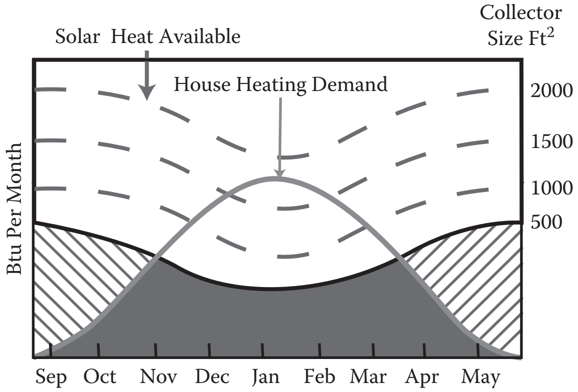
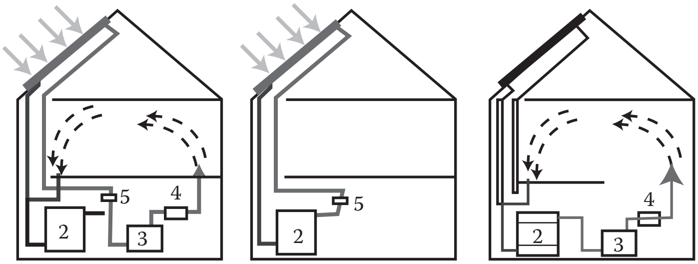


FIGURE 5.12 Size of collector and solar heat available versus house heating demand.



Heating from Collector

Storing Heat

Heating from Storage

FIGURE 5.13 Active solar heating system using air for heat transport.

exchanger. The heat is provided to the space when needed; however, the cost is too high to provide all the heating by solar energy (Figure 5.12), so an auxiliary heating system works in conjunction with the solar heating system. This means that during the fall and spring the solar system will provide all the heat, and during the coldest months the solar heating system will be sized to provide around 60% of the heat. During late spring, early fall, and the summer, the excess heat could provide assistance with domestic hot water.

Again, freezing of water is a problem in moderate and cold climates. There can be an open-loop solar heating system with a drain back at freezing temperatures, closed loop on the solar side with antifreeze or silicone fluid, or a closed loop or open loop with a two-tank system with heat exchangers.

A solar hot air system must move a larger volume of air than water to transport the same amount of heat. The operation modes depend on the relative temperatures of the collector, storage, and the space (Figure 5.13). The rock storage bin for an air system is sized for 2 to 3 days of heating. At present in the United States, there are no commercial active solar hot air systems for residences, although some special systems have been constructed for commercial buildings.

Most of the systems for active solar heating use flat-plate collectors, so they need to be installed at an angle to the horizontal that gives the best performance. For solar heating, the collectors should be placed at an angle around the latitude minus 15°; for year-round use, they should be at an angle close to the latitude; and for summer cooling, they should be at latitude plus 15°. NREL has a site that calculates the solar insolation for different types of collectors and for the flat-plate collectors at angles of latitude and angles of latitude plus or minus 15° (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/).

5.5.1 FLAT-PLATE COLLECTORS

Flat-plate collectors are the most common solar collectors for space heating and domestic hot water. The different components (Figure 5.14) can be fabricated from a variety of materials. In cold climates, two or three glazings are needed, and more insulation of the box is needed to reduce heat loss. The efficiency changes with number of glazings and the temperature differential between the outside and the absorber plate (Figure 5.15). In mild climates (no freezing) or for extending the swimming pool

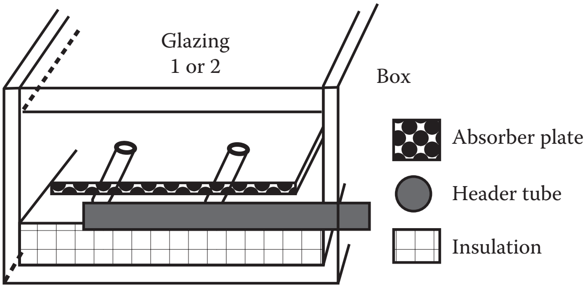


FIGURE 5.14 Components of flat-plate collector.

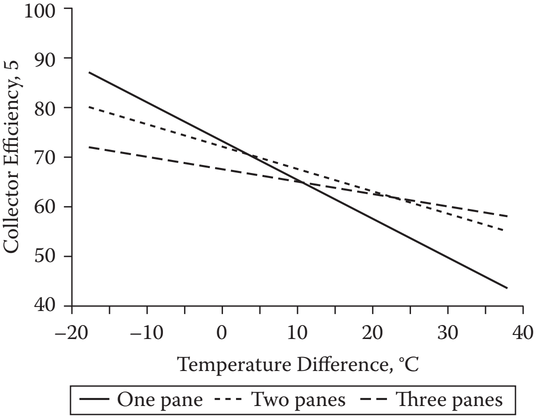


FIGURE 5.15 Daily collector efficiency for temperature difference between absorber plate and outdoor air. Notice efficiency is higher when temperatures are the same.

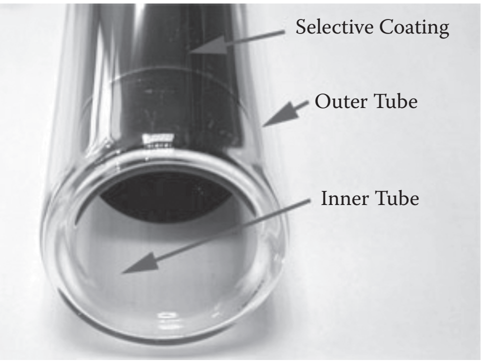


FIGURE 5.16 Evacuated tube collector.

FIGURE 5.17 Cross section of vertical hot air collector. Actual collector is in the background. From outside, fiberglass glazing, dead air space, absorber plate (selective coating), air channel, insulation with aluminum foil, plywood, and metal frame. Notice that glazing on the actual collector has become more translucent with UV aging. Light transmission is still about the same.

season, all that is needed is an absorber and a way to transfer the water. Absorbers can be copper, aluminum, or iron, with copper the most common for plates, tubes, and header pipes. Glazings can be plastic or glass with the box being aluminum, metal, or vinyl. Remember that different materials have different coefficients of expansion with temperature. If too dissimilar, joints and connections tend to come loose. Higher efficiencies can be obtained with evacuated glass tubes for the collector, with the inner tube having a selective coating (Figure 5.16). Glass glazings need to be able to withstand hail.

The components of a flat-plate air collector do not include tubes for absorber plate or header pipes (Figure 5.17). However, the air must come in contact with all parts of the back of the absorber plate (no stagnation areas), and the airflow needs to be slower.

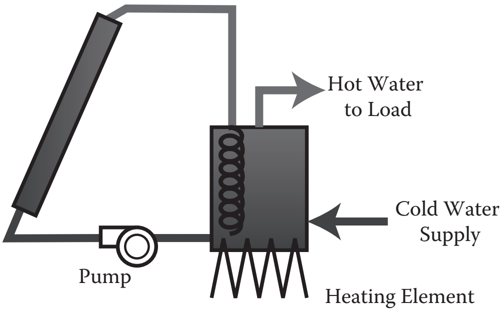


FIGURE 5.18 Solar hot water system. A differential temperature controller turns the pump on and off.

5.5.2 Domestic Hot Water

Generic types of systems that use flat-plate collectors to heat water are thermosiphon, closed-loop freeze-resistant, drain back, drain down, and air-to-liquid systems. The thermosiphon (passive) system does not use pumps as the tank, is generally insulated, and is above the collector; again, there is a check valve to stop reverse circulation [2]. However, placing a hot water storage tank in the attic presents problems, primarily due to weight and the possibility of leaks. For colder climates, a heat exchanger is necessary to keep the collector fluid separate from the water system.

In a direct circulation system, pumps circulate the household water through the collector. This works well in mid-temperature climates where it rarely freezes. In indirect circulation systems, pumps circulate a nonfreezing heat transfer fluid through the collector and a heat exchanger in the hot water tank (Figure 5.18).

Other types of systems are an integral collector-storage system (batch or bread box) and evacuated tube solar collectors. The batch hot water system has one or more black tanks or tubes in a collector box with a glazing, which preheats the water in conjunction with an ordinary hot water system; in some cases, it is the only source of hot water. The bread box is a simple system to build; however this system loses too much heat in cold climates.

There are commercial solar hot water systems available, and with different incentive programs, there is renewed emphasis on installing these systems. In Israel and Japan, solar hot water heaters are common. Components (Figure 5.19) can be purchased for the handy person to fabricate a personal system [3], and there are numerous sites with design information.

5.5.3 Swimming Pools

Solar hot water systems can also be used for swimming pools, and in many climates they do not require any glazing (Figure 5.20) because they are used during the summer and used to extend the swimming season; therefore, they are less expensive. Unglazed solar collectors are generally made of thermoplastic rubber (flexible rubber mat) or polypropylene plastic treated with an UV light inhibitor to extend the life of

FIGURE 5.19 Copper absorber fin with copper tube.

FIGURE 5.20 Solar hot water system for heating a swimming pool. Fixed tilt angle of array is 27° for summer sun at 35° N. Eight panels, thermoplastic, each 1.2 by 3 m (4 by 10 ft).

the panels. These solar panels may be either semirigid or have individual pipes. In areas with high evaporation rates, swimming pools have to be heated. For example, in the High Plains of Texas, the evaporation rate is over 2 m/yr due to wind and low humidity, so city swimming pools are heated with natural gas during the summer.

A free software program, Energy Smart Pools, is available from Reduce Swimming Pool Energy Costs [4]. The program lets owners analyze the current energy consumption of their pool and to project potential savings by energy management, pool cover, or solar heating.

5.6 ACTIVE COOLING

Active solar systems can cool a house during the summer; however, higher temperatures are needed to drive the absorption cooling cycle, so in general evacuated tubes or concentrating collectors are used but are more expensive. An absorption cooling unit uses two working fluids: an absorbent such as water and a refrigerant such as ammonia. The principle is the same as for refrigerators powered by burning natural gas. However, a flat-plate collector, with two or even three glazings, has to be very efficient. Approximately 50% of installed commercial air conditioning in Japan uses solar collectors.

5.7 DAYLIGHTING

Daylighting is the use of natural light for building spaces and is now recognized as an important part of residential, commercial, and industrial building design. Daylighting reduces the need for electric lights, and during the summer, it also saves on the heat load, thereby reducing the need for air conditioning. Indirect lighting can be spread throughout the structure using skylights, shaded windows, atriums, light pipes, reflecting shelves, fiber optics, and so on. Effective design strategies assist in optimizing the use of natural light. The strategies include the following: optimize the amount of daylight, preserve visual comfort, avoid direct sun, and preserve thermal comfort. A disadvantage of daylighting is the variability due to clouds and reflection from terrain and other buildings. Proper design of glazed areas has to take into account heat loss in the winter and heat gain in the summer. There are many images of daylighting available on Google Images. A number of Web sites explain, discuss, and give examples. For commercial and industrial buildings, consult http://www.gaia.lbl.gov/iea21/.

5.8 HYBRID AND OTHER

The Thompson system for a home consists of an open water system piped to the top of a corrugated metal roof. During sunny days in the winter, the water trickled down the south side of the roof, and then the heated water was used to heat the space at night. During summer, the water trickled down the north side of the roof at night, and then the cooler water was used to cool the space during the day. Of course, there are some problems that have to be eliminated, dirt and dust, too much evaporation in dry climates, and efficiency would be low in cold climates.

Roof spray for low, flat roofs of commercial buildings is effective for cooling in many areas. One problem is hard water clogging up the nozzles. Some people have advocated that 5 cm of water on flat roofs would greatly reduce cooling costs.

5.9 DRYING AGRICULTURAL PRODUCTS, LUMBER

In the developing world, agriculture products were and are dried by spreading them in the sun. Before cars were common in China, during harvest the asphalt highways were reduced to one lane due to grain being spread on the roads. In isolated areas, the sun is the only source for drying low-cost agriculture products such as fruit and vegetables for cash crops and to feed the village during the year.

TABLE 5.5
Advantages and Disadvantages of Agriculture Product Drying Methods

Type	Advantage	Disadvantage
Open air	No cost, no fuel	Dust, animals, ants, rain Labor to turn product over Collect at night? Longer time to dry Decreased effectiveness with high humidity
Firewood	Faster than open air	Cost of dryer box, fuel Forest degradation Smoke in product Labor for operation and maintenance
Electric	Drying well controlled Excellent quality	High cost, high operation cost Electricity not available
Solar	Fairly low cost No fuel cost Faster (three to four times) than open air Protected drying environment Built locally	New technology Requires proper operation

The benefits of dry food are preservation to eliminate or reduce spoilage from bacteria, yeast, and mold; dry food takes up less room; and it is lightweight and easier to transport. The disadvantages of traditional outdoor drying are relatively low drying temperatures and the high dependence on ambient temperature. Slower drying time causes greater spoilage, and health issues arise from dust and insects (ants and flies). Finally, birds, squirrels, rodents, and lizards eat the food.

Drying of agriculture products by different methods (Table 5.5) indicated that solar drying is the best option for small-scale farmers. The solar thermal collector is around 60% efficient. The benefits of the solar dryers are as follows

Dries food between 50 and 80°C, which is a good range for drying and pasteurization
Reduces moisture content to 10–20%
Faster drying time

The two methods of solar drying are direct (Figure 5.21) and indirect (Figures 5.22 and 5.23). The benefits of the indirect solar dryer are as follows:

No direct UV rays (UV light degrades vitamins and color)
No need for sulfur, blanching
Better control of drying process; regulation of temperature by passive or active venting

FIGURE 5.21 Direct solar dryer for fruit and vegetables, Kabul, Afghanistan. Solar dryer designed by Robert Foster. (Courtesy of Robert Foster.)

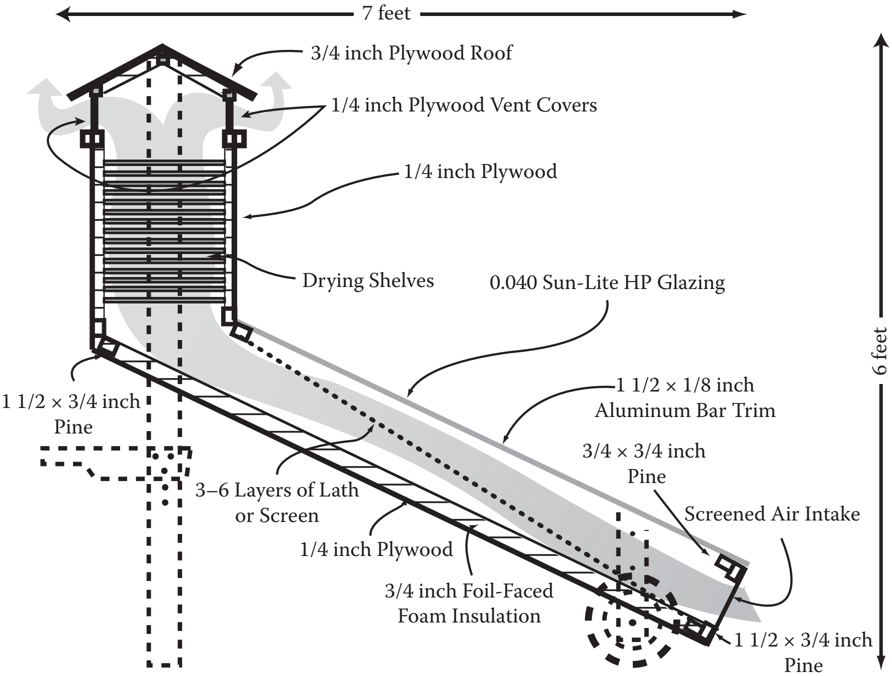


FIGURE 5.22 Diagram of indirect solar food dryer, based on design, Appalachian State University, 1997.

FIGURE 5.23 Indirect dryers built at local shop, Kabul, Afghanistan. In 2009, there were 130 built. Left to right: Khatera Obaid, Robert Foster, and carpenter Mohammad Hakeen Popa. (Courtesy of Mohammad Salim.)

In either method, almost all the components can be obtained locally and built locally (Figure 5.23).

Drying lumber can be a complex operation to reach the desired quality: wood without cracks. Lumber can be air dried, but in many locations the humidity is too high, so a kiln is used. There are a number of designs for solar kilns [5,6], which in general have a sloping roof with a glazing and a big door for access. Slope of the roof depends on latitude and ease of construction. A solar kiln should be relatively inexpensive and have simple operation.

Solar kilns designed, constructed, and tested at Virginia Tech [7] will dry a load of lumber in around 1 month in the medium sunny climate around Blacksburg, Virginia. The kilns have a sloping roof of clear, greenhouse-rated, corrugated polyethylene, four insulated walls, and an insulated floor (Figure 5.24).

5.10 SOLAR COOKERS

Many people in underdeveloped countries use biomass (wood, charcoal, and dung) for cooking; with the problems of deforestation and desertification, children and women spend an inordinate amount of time collecting wood, children have less for school, and health problems from smoke and fumes in confined spaces occur. Solar cookers [8] have now become part of the solution with over 2 million in use worldwide.

Of course, solar cookers depend on a climate with enough sunshine, that is, climates that are dry and sunny for at least 6 months of the year. These regions are generally within 40° of the equator. Solar cookers will not work during cloudy and inclement weather, and because most solar energy occurs between 1000 and 1400, the solar

(a)

(b)

FIGURE 5.24 Solar kiln for drying wood, (a) front view; (b) back view shows load of lumber with the baffle up. (Courtesy of Wood Science and Forest Products, Virginia Tech University.)

cooker can be used for two meals per day, noon and evening. The principles are simple: collection of radiant energy to heat a cooking vessel and retention of heat. Solar cookers can be constructed primarily from locally available materials, and many are portable.

Solar cookers require a change in method of cooking due to moderate temperatures and time for cooking. Temperatures are within the range for cooking food, 82 to 91°C, which help preserve nutrients and kill bacteria and viruses (when heated to 71°C). However, as noted this may take a period of time, up to 1 or more hours, to fully cook the food [9]. Because of the moderate temperatures, the food can be placed in the cooker and left unattended. Dark, shallow, thin, metal pots with tight-fitting lids to hold in the heat and moisture work the best.

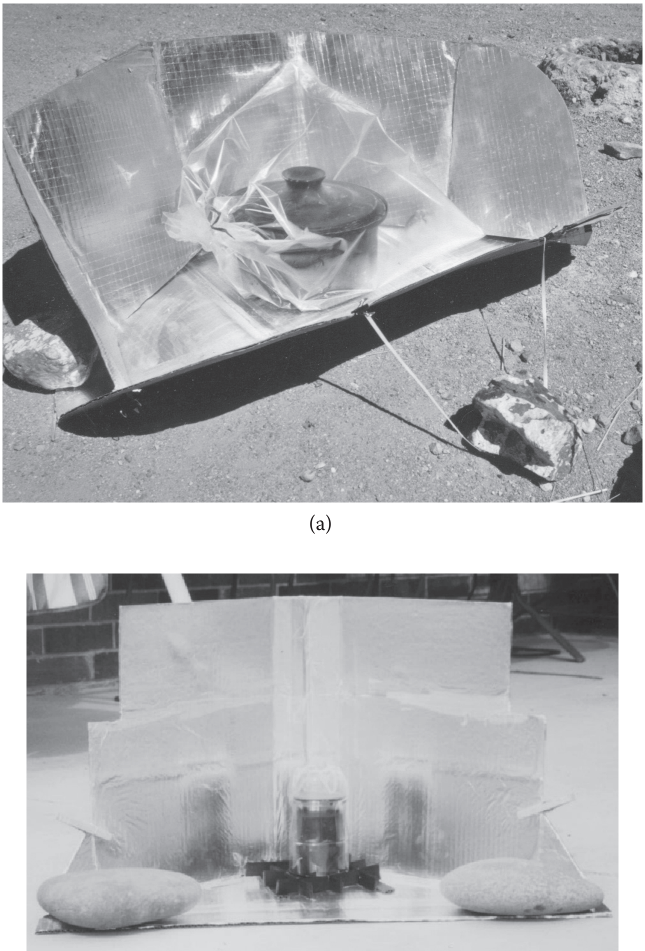
FIGURE 5.25 Box solar cooker. (Courtesy of Solar Cookers International, http://www.solarcookers.org.)

The three main types of cookers are box, panel, and curved concentrator, although there are lots of variations on these, and even large-scale solar cookers have been developed for institutions [10]. For example, a dark pot inside a transparent plastic bag or a large inverted glass bowl can serve as a solar cooker. Box cookers (Figure 5.25), also referred to as bread box cookers in the past, reach moderate to high temperatures and can accommodate multiple pots. One or more surfaces can reflect additional sunlight into the box cooker to increase the temperature. Panel cookers (Figure 5.26) have panels that reflect radiation onto the cooking pot, which can be inside a plastic bag or under a glass bowl. The advantage of the panel cooker is that it can be built in an hour, and the cost is low. Curved concentrating or parabolic cookers (Figure 5.27) reach higher temperatures, which means they cook faster; however, they require frequent adjustment and supervision. Numerous plans and kits are available for solar cookers [11].

5.11 WATER PURIFICATION

Unsafe water is a major health problem as over $1 * 10^9$ people do not have potable water. Preventable waterborne diseases account for approximately 80% of illnesses and deaths in the developing world. Microbes in water that cause diseases are killed by exposure to water heated to 65°C for around 20 min (pasteurization). At around 70°C, milk and other foods are pasteurized.

Solar cookers can pasteurize water for a family at a rate of about 1 L/h. Water can be brought to a boil. One reason that people are told to boil water is that thermometers


(a)

(b)

FIGURE 5.26 Panel solar cookers: (a) pot in plastic bag and rope tied to rock is to keep cooker in place in wind (Courtesy of Solar Cookers International, http://www.solarcookers.org); (b) student project for solar class.

are not readily available in many places, and the boiling action serves as the temperature indicator. Water can be boiled in all three types of cookers; however, the time is much shorter for a concentrating collector. To make potable water, it only has to be pasteurized, not sterilized. A reusable water pasteurization indication [10] can be used to determine when water heated by solar or conventional means has reached appropriate temperatures to make it safe.

Solar stills (Figure 5.28) are another way of producing potable water, this time by distillation [12]; this is used for undrinkable (brackish, contaminated) water. This method also eliminates microbes. As the water evaporates (Figure 5.28), it condenses on the glass surface of the collector and drains down to a collecting reservoir. Water is

FIGURE 5.27 Each family at the Solar Energy Research Institute, Lhasa, Tibet, has a concentrating solar cooker to heat its teakettle.

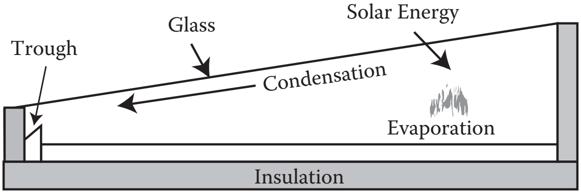


FIGURE 5.28 Diagram of solar still.

added once per day, generally manually, and excess water drains out the overflow port. This also reduces salt buildup, a ratio of around 3/1 for input versus collected potable water. Of course, production depends on solar input, and with a good resource, production rates will vary from 2 L/m^2 per day in the winter to 6 L/m^2 per day in the summer. A solar still (Figure 5.29) (standard glass patio door, 1.1 by 2.5 m) produced around 10 L per day in the El Paso, Texas, region [13]. Cost of materials for this size solar still is around $300. Again, there are designs on the Internet for building solar stills.

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2. Daniel K. Reif. 1983. *Passive solar water heaters, how to design and build a batch system*. Brick House, Amherst, NH.

FIGURE 5.29 Solar still. (Courtesy of El Paso Solar Energy Association.)

3. Russell H. Plante. 1983. *Solar domestic hot water, a practical guide to installation and understanding*. Wiley, New York.
4. RSPEC. Energy smart pools software. http://www.rlmartin.com/rspec/software.htm.
5. Build It Solar. Site provides various links. http://www.builditsolar.com/Projects/Wood-Drying/wood_kiln.htm.
6. M. B. Gewali and R. Bhandari. Solar drying technology packages developed at Recast. http://www.retsasia.ait.ac.th/Publications/WRERC%202005/RECAST-WRERCE-final.pdf.
7. Design and operation of a solar-heated dry kiln. http://www.woodscience.vt.edu/about/extension/vtsolar_kiln.
8. B. Prosser Kerr. 1991. The expanding world of solar box cookers. http://solarcooking.org/kerr.htm.
9. Solar cooking frequently-asked questions. http://solarcooking.org/solarcooking-faq.htm.
10. Solar Cookers International. http://www.solarcookers.org.
11. Build a solar cooker. http://solarcooking.org/plans/.
12. Solar still basics. http://www.solaqua.com/solstilbas.html.
13. Solar water purification project. http://www.epsea.org/watersolar/purification.

RECOMMENDED RESOURCES

LINKS

Heat transfer and properties of windows. http://www.cecer.army.mil/techreports/DEA_NEW/dea_new.fle-02.htm.

Solar radiation data manual for flat plate and concentrating collectors. http://rredc.nrel.gov/solar/pubs/redbook.

U.S. Solar Radiation Resource Maps. http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas.

PROJECTS, TECHNICAL INFORMATION, AND PHOTOS

Buena Vista. http://www.sunroom.com.

Kalwall. http://www.kalwall.com/main.htm.

National Renewable Energy Laboratory. Trombe walls in low-energy buildings: practical experiences. 2004. http://www.nrel.gov/docs/fy04osti/36277.pdf.
Sun-Lite HP. http://www.solar-components.com/sun.htm#sgmat.
Sunroom-sunroom.com home page. http://www.sunroom-sunroom.com.

SOLAR HOT WATER

Energy Efficiency and Renewable Energy, DOE. http://www.energysavers.gov/your_home/electricity/index.cfm/mytopic=12850.
Florida Solar Energy Center. http://www.fsec.ucf.edu/en/consumer/solar_hot_water.
Integration of Renewable Energy on Farms. Solar thermal-water heating. http://www.farm-energy.ca/IReF/index.php?page=water-heating.
National Renewable Energy Laboratory. http://www.nrel.gov/learning/re_solar_hot_water.html.
Reduce swimming pool energy costs. http://www.rlmartin.com/rspec/index.html.

SOLAR AIR CONDITIONING

Austin solar uses parabolic troughs. http://www.austinsolarac.com/product.htm.

DAYLIGHTING

Daylighting Collaborative. http://www.daylighting.org.
National Institute of Building Sciences. http://www.wbdg.org/resources/daylighting.php.

SOLAR DRYING

Commercialisation of the solar dryer. http://www.areed.org/training/technology/solar_dryer/dryer_2.pdf.
Integration of Renewable Energy on Farms. Solar drying. http://www.farm-energy.ca/IReF/index.php?page=air-heating-solar-drying-technology.

SOLAR COOKERS

Solar Cookers International. http://www.solarcookers.org.

PROBLEMS

For Amarillo, Texas, heating is needed from mid-October through mid-May. There are 887 heating degree-days for January.

1. Calculate, by month, the season heating gain for a single-pane window (south facing), 1.2 m by 2.5 m, for Amarillo, Texas.
2. Calculate, by month, the season heating gain for a double-pane, low-e window (south facing), 1.2 m by 2.5 m, for Amarillo, Texas.
3. Calculate the season heating gain for the south-facing windows at your house.
4. Is the single-pane window in problem 1 a net heat gainer for January? You will have to do the heat loss calculation for January.

5. Is the double-pane window in problem 2 a net heat gainer for January? You will have to do the heat loss calculation for January.
6. Would you buy triple-pane, low-e windows for a home in the area of Amarillo, Texas. Justify your answer (yes or no will not suffice).
7. What are the advantages of Sun-Lite as a glazing material? Go to their Web site for information (http://www.solar-components.com/sun.htm).
8. What are the *R* values for a wall composed of Kalwall. Go to their Web site for information (http://www.solar-components.com/panels.htm).

6 Photovoltaics

6.1 INTRODUCTION

A photovoltaic (PV) cell converts sunlight directly into electricity. A number of materials are photoelectric: Light is absorbed, and an electron acquires kinetic energy to move it to another energy level within the material. Today, the primary materials for PV cells are semiconductors, although researchers are trying other materials, even organic polymers. A PV cell is used in things from small items such as calculators and watches to large installations for electric utilities. Even though PV systems are expensive, there are a number of applications in which they are cost effective, especially for stand-alone systems some distance from the utility grid, mobile jobs such as construction signs, and even for low power (50–200 W) close to the grid. A PV system has the following advantages and disadvantages:

Advantages	Disadvantages
High reliability	High initial costs
Low operating costs	Variability
Modularity	Storage increases costs
Low construction costs	Lack of infrastructure in remote areas

PV has another major advantage for the production of electricity because PV cells and wind do not require water, in contrast to conventional thermal steam plants, even those powered by nuclear reactors.

6.2 PHYSICS BASICS

Charge is an inherent property of particles, and charged particles interact by electromagnetic (EM) interaction, which is strong in terms of force. Charge comes in units, positive or negative, equal to the value of the charge on an electron. Atoms are neutral due to an equal number of positive charges from protons in the nucleus and negative charges, electrons, that surround the nucleus. For our purposes in describing the electrical properties of materials, the nucleus stays in the same place because it has almost all the mass, and only the electrons move.

Most properties (mechanical, electrical, thermal, chemical, biological) of materials can be explained by their electron structure and, in general, by the outer electron structure of the atoms or molecules. Only the basic information on electricity is covered as beginning physics textbooks cover electricity and magnetism in more detail.

Charge Q or q is measured in coulombs (C).

One electronic charge = $1.6 * 10^{-19}$ C, positive or negative. Notice that 1 C is a large number of unit charges.

Electric fields **E** are created by charged particles, and if a charged particle is placed in an external electric field (due to other charges), there is a force on it, which will make it move. Notice that **bold** indicates a vector; it has both magnitude and direction. A scalar only has magnitude (e.g., temperature).

$$\mathbf{F} = q * \mathbf{E} \tag{6.1}$$

Then, energy or work (see Equation 2.1) is available as the charged particle is moved through some distance. The electric potential V is the energy/charge.

$$\mathbf{V} = W/q, \text{ volt (V)} \tag{6.2}$$

Then, the equation can be rearranged, Energy = $V * q$. An electron volt (eV) is the energy one electron would acquire from moving through a potential of 1 V, so 1 eV = $1.6 * 10^{-19}$ joules.

The electrical properties of materials are divided into three general classes: conductors, semiconductors, and insulators. Metals (e.g., copper and gold) are good conductors, and wood and glass are good insulators. However, if there is enough excess charge of one type, then all materials will break down and conduct electricity. You do not want to be the lightning rod in a thunderstorm.

Current is the flow of charge moving past a point in 1 s:

$$\mathbf{I} = dq/dt, \text{ ampere (A)} \tag{6.3}$$

Direct current (DC) is the flow of charge in only one direction (convention is from positive to negative), and alternating current (AC) is the flow of charge in both directions, variable in terms of cycles or frequency (number/time). In the United States, the frequency of the electric grid is 60 Hz, and in Europe it is 50 Hz (hertz = number of cycles/s). For conductors and semiconductors, if a voltage is applied across the material, there will be a current. However, there will be a resistance to the flow of that current. Resistance is measured experimentally, and it will have a low value for metals and a large value for insulators.

$$R = V/I, \text{ ohms } (\Omega) \tag{6.4}$$

Ohm's law is the linear relationship of voltage and current for metals, $V = I * R$ Then, the power, which is energy/time, can be obtained from the voltage and current.

$$\text{Power} = V * I, \text{ watt} \tag{6.5}$$

Example 6.1

An element has a resistance, $R = 2\ \Omega$, and a voltage, $V = 12$ V, applied across it. What is the current and power?

$$I = V/R = 12\ \text{V}/2\ \Omega = 6\ \text{A}$$

$$P = V * I = 12\ \text{V} * 6\ \text{A} = 72\ \text{W}$$

Notice: For problems that have units, answers have to have units.

6.3 ENERGY BANDS

In materials, the energy states for electrons are close together, so they form bands that explain the three main types of material: Conductors have free electrons that can move easily under an applied electric field, semiconductors have a few electrons that can move, and insulators have no free electrons (Figure 6.1). In a conductor, the conduction band is partially filled with electrons, so there are energy states available for free electrons; therefore, metals are good conductors.

In a semiconductor, at room temperatures some electrons have enough energy to get into the valence band, leaving a hole in the conduction band. The band gap is small, on the order of an electron volt. Another way the electron can obtain enough energy to move from the conduction band to the valence band is by the absorption of a photon (EM radiation with enough energy).

In an insulator, such as glass, there are not any free electrons as all electron states are filled in the conduction band, and the band gap energy to the valence band is large, so there are no electrons in that band.

In a semiconductor, the current is explained by the movement of electrons (negative) and holes (positive). The movement of electrons in the conduction band fills an energy state, which then leaves an empty state, so it is easier to describe that current by the movement of holes, which have an equivalent positive charge. The number of electrons in the valence band can be increased by doping the silicon with phosphorus, which has an extra electron for bonding (n, negative-type semiconductor), or by increasing the number of holes in the conduction band by doping the silicon with boron, which is deficient by one electron for bonding

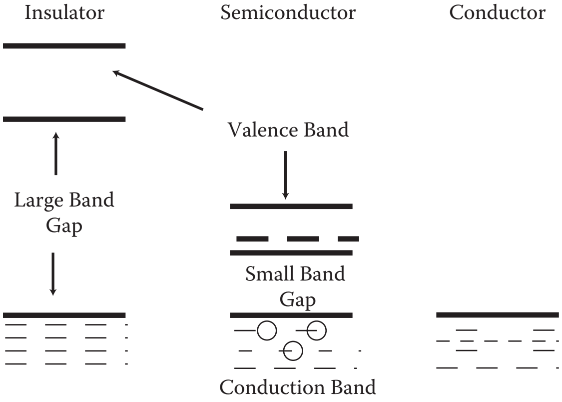


FIGURE 6.1 Electron energy states form bands in materials.

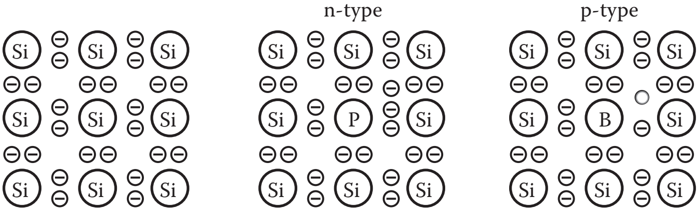


FIGURE 6.2 Semiconductors doped with phosphorus and boron. Electrons are −, and holes are ○, which are treated as a positive charge with a mass essentially the same as the electron mass.

(p, positive-type semiconductor) (Figure 6.2). Either one increases the electrical conduction. The n and p materials are fabricated in layers and islands to create diodes, transistors, integrated circuits (i.e., solid-state electronics).

Electromagnetic (EM) radiation is described as waves with the electric and magnetic fields varying in time and wave travels at the speed of light. The other way to describe phenomena is by particles: quantization. So, EM radiation occurs in units, called photons, which have no mass and travel at the speed of light. The energy of a photon is proportional to the frequency (Equation 3.2), so x-ray photons have a lot more energy than visible photons, and blue photons have more energy than red photons.

Photons are produced and absorbed in materials but always in those units of energy. So, when a semiconductor has a certain band gap, photons with less energy than the band-gap energy cannot be absorbed. When photons with energy equal to or greater than the band gap are absorbed, an electron is shifted to the valence band, which leaves a hole in the conduction band. Excess energy becomes heat. Many times, physicists like to have numbers without powers of ten, so electron volts (eV) are used in describing semiconductors.

6.4 PHOTOVOLTAIC BASICS

The solar cell (Figure 6.3) is fabricated by having an n and p layer, which is a junction. At the junction, the excess electrons in the n-type material flow to the p type, and the holes thereby vacated during this process flow to the n type. The junction acts as a battery, creating an electric field at the surface where they meet. This field causes the electrons to move from the semiconductor out toward the surface and make them available for the electrical circuit. At the same time, the holes move in the opposite direction, toward the positive surface, where they await incoming electrons. So, when photons are absorbed by the PV cell, they create more electrons and holes, which become available for a current for an external load [1].

To improve efficiency, the materials should be modified to have band-gap energies for photons in the visible range, where the most energy is available from the sunlight. The spectrum from infrared to ultraviolet (UV) covers a range of about 0.5 to about 2.9 eV. For example, red light has energy of about 1.7 eV, and blue light has energy of about 2.7 eV. Effective PV semiconductors have band-gap energies ranging from 1.0 to 1.6 eV. Band gaps in semiconductors are in the 1 to 3 eV range. For example, the band-gap energy of silicon is 1.1 eV.

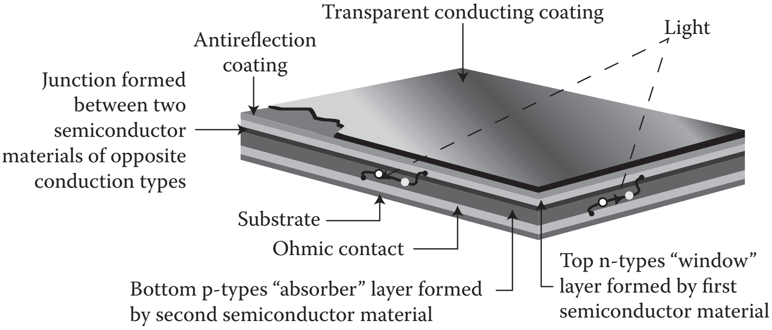


FIGURE 6.3 PV cell formed by n and p layers. (Diagram from Photovoltaics, Solar Energy Technologies Program, EERE, DOE, http://www1.eere.energy.gov/solar/photovoltaics_program.html.)

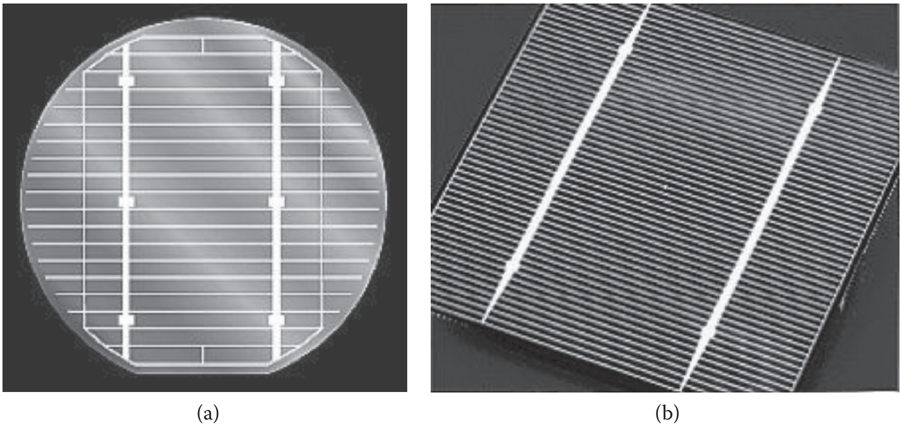

(a)
(b)

FIGURE 6.4 Examples of PV cells: (a) older cell type, wafer cut from ingot of silicon; (b) polycrystalline cell, wafer cut from cast square ingot of silicon. (From National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), http://www.nrel.gov/ncpv.)

The solar cell (Figure 6.4) is the basic building block of a PV system. Individual cells can vary in size from about 1 to 10 cm. However, one cell only produces 1–2 W, which is not enough power for most applications. So, cells are combined into a module, modules into a panel, and panels into arrays for large power applications. Thin-film materials like amorphous silicon and cadmium telluride can be made directly into modules. Another manufacturing process is drawing of ribbons of semiconductor material. Finally, research on other materials and manufacturing processes is progressing.

The conversion efficiency of the PV cell is the ratio of electrical energy produced over the insolation on the cell. Today, PV devices convert 7–17% of light energy into electric energy; however, multiple layers and other improvements have raised efficiencies into the 35–40% range for laboratory experiments. About 55% of the energy of sunlight cannot be used by most PV cells because this energy either is below the band gap or carries excess energy, which results in heat. Another way to improve efficiency is using multiple p/n junctions, which have efficiencies as high as 35%. Cell efficiencies for silicon decrease as temperatures increase, and higher temperatures also threaten the long-term stability of the material. Therefore, PV cells must be kept cool, especially for concentrating collectors.

Cell types are as follows:

Single crystal: The most expensive production method, it is reliable, and its module efficiencies average 10–12%.
Semicrystalline: Production costs are lower and efficiencies are lower, module efficiencies are 10–11%; however, cell performance may degrade over time.
Polycrystalline thin films: These are less efficient due to boundaries between crystals.
Amorphous: Material is vaporized and deposited on glass or stainless steel; production costs are lower; module efficiencies are 7–8%; it degrades over time.
Thin film: Created by deposition or thin ribbon (Evergeen Solar, 10 cm wide, which are then cut into wafers).

6.5 PERFORMANCE

Cells are combined into modules, and the modules have outputs from 10 to 300 W. The amorphous and thin films are cut to panel size. A typical module or panel consists of

Transparent top surface: usually glass
Encapsulant: usually thin sheets of ethyl vinyl acetate that hold together the top surface, solar cells, and rear surface
Rear layer: thin polymer sheet, typically Tedlar, to seal module
Frame: typically aluminum
Electrical connection

The performance of a module is given by the current-volt characteristics (Table 6.1). The open circuit, no current, gives the maximum volts, and a short circuit, no voltage, gives the maximum current. Remember power is volt * current, and the maximum efficiency is at the knee of the curve (Figure 6.5). The power curves will change with temperature, and maximum power output will decrease.

The performance ratings of modules include

Peak watt (W_P): Maximum power under laboratory conditions of high light level and low temperature.
Normal operating cell temperature (NOCT): Measures nominal operating cell temperature after module comes into equilibrium with a specified ambient temperature. Results in a power output lower than W_P.
AMPM standard: Measures performance for a day, not peak value, based on standard solar global-average day in terms of light, ambient temperature, and mass of air (primarily elevation). Solar insolation on a sunny day is greater at higher elevations.

TABLE 6.1
Example Specifications for a PV Module, 53 W_P

Operating Point	
P	53 W_P
VMP (at peak power)	17.2 V
IMP (at peak power)	3.08 A
V_{OC} (open circuit)	21.5 V
I_{SC} (short circuit)	3.5 A
Standard test conditions (STC)	1,000 W/m², 25°C

NOCT would be around 50°C with ambient temperature at 25°C.

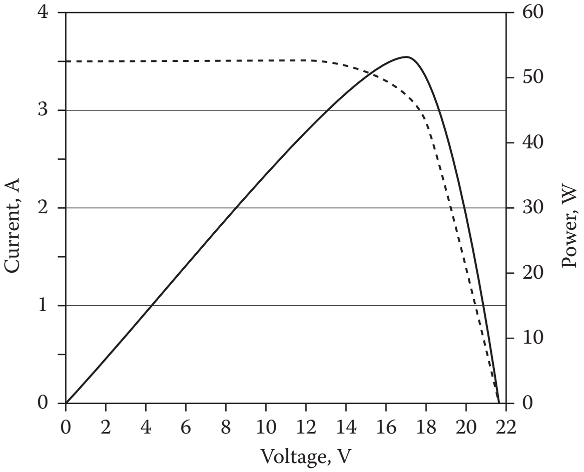


FIGURE 6.5 Typical PV cell I-V curve (power indicated by solid line). Notice that maximum power occurs at the knee in the I-V curve.

Some PV cell specifications provide power curves at 1 and 0.5 Sun (incident energy of 1,000 W/m² and 500 W/m²), which represents full-sun and cloudy day performance.

Four factors affect array performance:

I-V operating point (load matching for maximum power)
Solar intensity (Figure 6.6)
Operating temperature (Figure 6.7)
Sun angle

A PV system provides all the power requirements of an application. The system includes one or more PV modules, power conditioning or controller, wires and other electrical connectors, and the load. Batteries for backup power or float are an option. The simplest PV system consists of flat-plate modules, panels, or arrays in a fixed

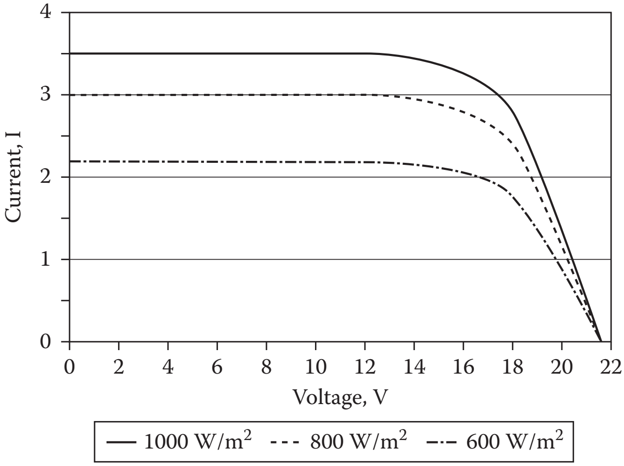


FIGURE 6.6 PV cell performance as a function of incident radiation.

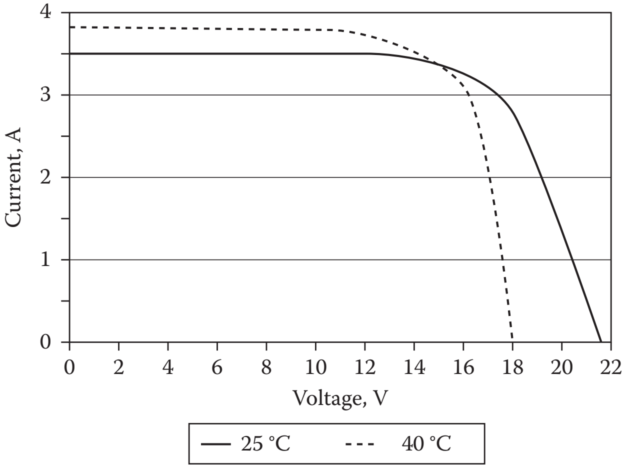


FIGURE 6.7 Performance of a PV cell due to temperature.

position. The advantages are no moving parts and lightweight structure. Of course, there is less conversion of light to electricity as the angle of the sun to the fixed modules changes during the day and by day of the year (season).

The performance of a PV cell/module can be described in terms of its energy conversion efficiency, the percentage of incident solar energy (input) that the cell converts to electricity (output) under standard conditions of 1,000 W/m^2, 25°C, one air mass (sea level). In 2007, the average energy conversion efficiencies for cells/modules were crystalline silicon (single crystal), 17%; crystalline silicon (cast), 14%; crystalline silicon (ribbon), 12%; thin film (amorphous silicon), 8%; thin film other (special photovoltaic material such as CdTe and CuInGaSe), 1%; and

TABLE 6.2
Average PV System Component Efficiencies

PV array	80–85%
Inverter	80–90%
Wire	98–99%
Disconnects, fuses	98–99%
Total grid tied (AC)	60–75%
Batteries, round trip	65–75%
Total off grid (AC)	40–56%
Total off grid (DC)	49–62%

concentrator PV systems, 35%. Research and development are focused on improving cell/module efficiencies and reduction of manufacturing costs. Cell efficiencies of 40% have been reported for multijunction semiconductors in the laboratory.

The overall performance and efficiency is the conversion of sunlight to the end product, electricity, water pumped, potable water produced, and so on. Generally, the end product is electricity, DC (direct current) for stand-alone systems or AC (alternating current) for village power or grid connected. In any case, there are efficiencies (Table 6.2) for the balance of the system (BOS): charge controllers, storage (generally batteries), inverters and converters, pumps, and so on. In the final analysis, the important factors are energy produced and the cost of that energy for the PV system and the competitive cost of energy from other sources, fossil fuels, and even other renewable energy sources.

6.6 DESIGN CONSIDERATIONS

Primary considerations for design of a PV system are the load, solar resource (percentage of hours of sunshine) by month or by season of load, and storage (how much), and for stand-alone or village power, considerations are also for load growth over the next 10 yr [2,3].

Stand-alone or isolated systems generally have a charge controller and batteries; however, some systems, such as water pumping, may only have a controller. The size of PV cell and batteries depend on load and how much storage is needed.

For grid connection [4], the PV system is a parallel source to the grid, and an inverter changes the DC to AC at the proper frequency (Figure 6.8). All the energy

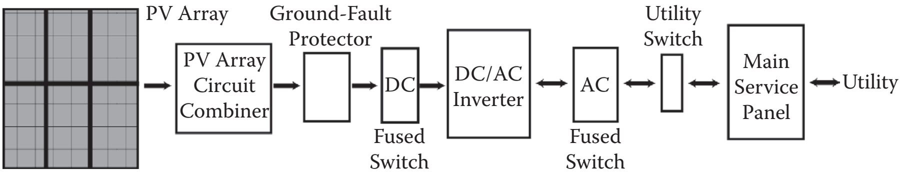


FIGURE 6.8 Typical PV system connected to the utility grid.

produced by the PV system may be used on site, and depending on the size of the PV system, sometimes energy may be fed back to the grid. If there is a fault in the utility grid, the inverter keeps the PV system disconnected from the grid for safety reasons. If the end user wants power if the grid is down, then battery storage is added, and more stringent controls are needed for disconnecting and reconnecting to the utility grid and the possibility of only powering critical loads.

Then, there are PV power plants for which the PV system is another generator on the grid. These systems range from 300 kW to even megawatts.

6.6.1 Sizing

The solar resource will vary widely depending on the location; however, most temperate and tropical locations have adequate resources. Locations where there is continuous cloud cover for weeks present challenges, so PV systems would have to be larger. Power on overcast days is around 10% of that on sunny days with clear sky. Concentrating solar energy systems need direct sunlight, so they are located in excellent solar resource areas.

Maps and tables are available (see Chapter 2) for average monthly solar insolation (kWh/m^2) for many regions of the world. Insolation data that are closer to the project site should be used and should take the conservative estimate for the amount of solar resource. The PV system is designed for the seasonal solar resource, seasonal load (or month of highest demand), or yearly average.

The surface of the module or array will receive both direct and diffuse radiation, and on clear days most energy is direct, while on cloudy days most energy is diffuse. The amount of radiation received (surface perpendicular to the sun) on a clear day varies by time of day due to difference of path length through the atmosphere of the Earth (Figure 6.9). For practical considerations, an average day is used (power/area or kWh/area). Since the standard power used for sunlight is 1,000 W/m^2, then over

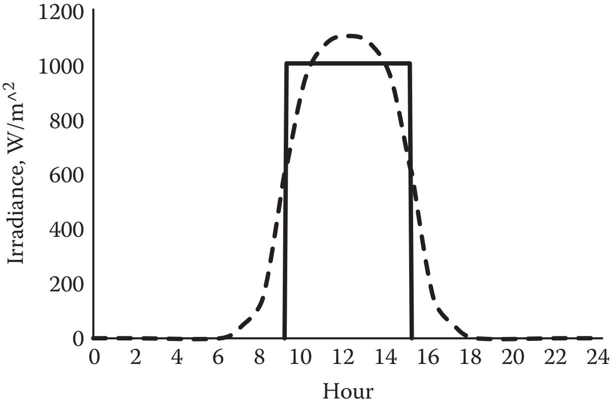


FIGURE 6.9 Irradiance (dashed line) and corresponding or equivalent sun hours (solid line) for average day.

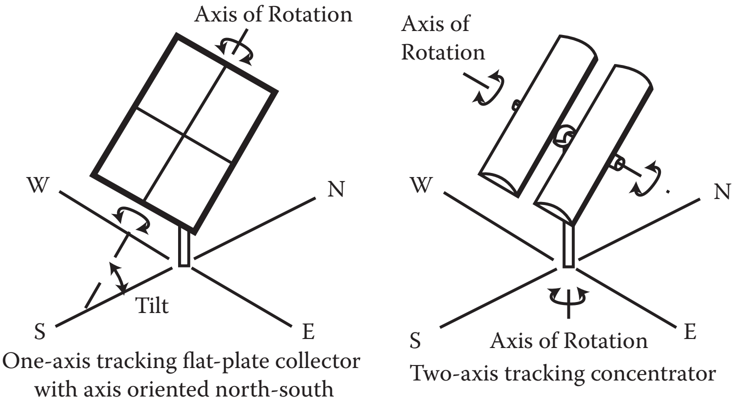
1 h that would be 1 kWh/m^2, sometimes referred to as peak sun hour or sun hour. So, on a clear day there would be 6 sun hours (dashed line in Figure 6.9). In temperature zones, the number of peak or sun hours will vary by season; of course, for fixed arrays, less energy is absorbed due to the angle factor (cosine factor) between array and sun position.

For a fixed-tilt array, placement of the array with the azimuth south (north in the Southern Hemisphere) and tilt angle at the latitude will give the best performance. However, the tilt angle is not too critical as tilt angle within 10° of the latitude will give about the same results—just the peak values occur at different times of the year. One way to increase energy output is by tracking or even by changing tilt angle for a fixed array by season.

6.6.2 TRACKING

There are one- and two-axis tracking systems. Common PV systems have a flat plate and fixed angle (tilt), so one way to improve the performance of flat-plate collectors is by tracking the sun (Figure 6.10), especially for photovoltaic panels since they are expensive. Methods for improving performance by tracking are as follows:

A manual change of panel tilt from summer to winter is used.
One-axis tracking: The axis of rotation can be either the north–south or east–west line.
Two-axis tracking: One possibility is to have passive east–west tracking and change the tilt angle by month manually. Otherwise, it requires an active tracking mechanism, with inherent problems of power and moving mechanical parts. One method of control is to track the sun, and a newer method of control is to use a geographic position system.



One-axis tracking flat-plate collector with axis oriented north-south

Two-axis tracking concentrator

FIGURE 6.10 Flat-plate collectors with one- and two-axis tracking. (Diagrams from National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), http://www.nrel.gov/ncpv.)

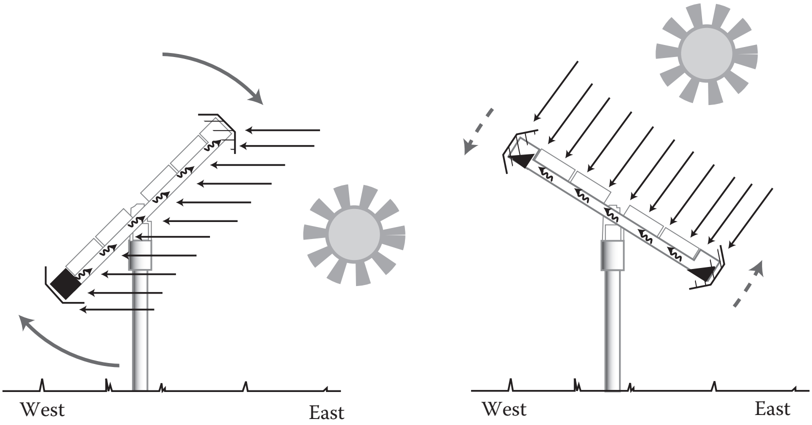


FIGURE 6.11 Passive tracking for flat-plate collectors. (Diagram from Zomeworks, http://www.zomeworks.com.)

Passive trackers use two canisters where the solar direct radiation increases the vapor pressure, driving liquid from one side to another (Figure 6.11) to keep panels oriented toward the sun. Passive tracking systems do not require extra energy or motors and gears (which require more maintenance). However, in windy areas, passive trackers may not work well as the wind force is larger than the passive tracking force. Tracking collectors produce 25–45% more power in the summer and pump up to 50% more water than a fixed flat-plate, PV water-pumping system.

6.6.3 Estimation of Energy Production

Generally, the energy production for the PV system is estimated by month from average day insolation for a flat plate. Some databases [5] have values (kWh/m^2/day) for different tilt angles (0, latitude, latitude ± 15°, and 90°), while the National Renewable Energy Laboratory (NREL) has maps by month for a flat plate tilted at latitude angle (http://www.nrel.gov/gis/solar.html).

For a fixed array, the energy day can be estimated from average day and area.

$$E_D = E_S * E_C * IN_D * A \tag{6.6}$$

where E_S is the system efficiency (includes derating for operating temperature); E_C is the cell efficiency, which depends on type; IN_D is the average insolation at the tilt angle (month or annual average); and A is the array area.

Another method is to use the average-day insolation (map value, tilt at latitude) and the power rating of the module.

$$E_D = E_S * RP * HS \tag{6.7}$$

where RP is the rated power, and HS is the average number of sun hours.

Example 6.2

Estimate the energy output for a 0.5-kW PV system for Amarillo, Texas, for the month of January. The system is as follows: BP solar, crystalline silicon, 225-W module, 1.65 by 1 m, area = 1.65 m^2; array of two modules tilted at latitude. See Reference 5 for Amarillo data; January average day = 4.9 $kWh/m^2/day$. $E_S = 70\%$, $E_C = 17\%$. Use Equation 6.6.

$$\text{Energy} = 0.7 * 0.17 * 4.9\ \text{kWh}/(\text{m}^2\ \text{day}) * 3.3\ \text{m}^2 * 31\ \text{days} = 60\ \text{kWh}$$

Cell efficiency = 17%, and system efficiency is 70% (better output because of colder weather), so estimated energy is 60 kWh.

If you need more energy, use more modules, modules with higher rating, or a tracking system.

Example 6.3

As a rough estimate, two modules = 450 W, average of 5 peak hours/day, $E_S = 70\%$. Use Equation 6.7.

$$E_D = 0.7 * 450\ \text{W} * 5\ \text{h} = 1.5\ \text{kWh/day}$$

$$\text{Energy/month } E = 1.5 * 30 = 45\ \text{kWh/month};$$

$$\text{Energy/year } E = 1.5 * 365 = 550\ \text{kWh/yr}$$

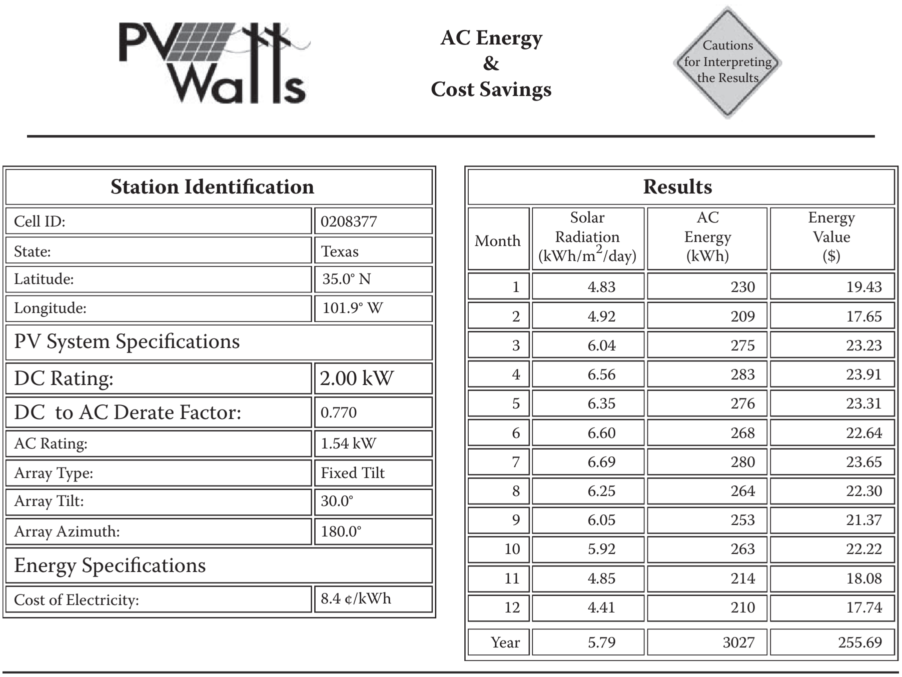
The PVWatts calculator [6] creates hourly performance simulations that provide estimated monthly and annual energy production and power (kilowatts) for grid-connected systems for locations throughout the world. Users can select a location and choose to use default values or their own system parameters for size, electric cost, array type, tilt angle, and azimuth angle.

The PVWatts calculator determines the solar radiation incident on the PV array and the PV cell temperature for each hour of the year using typical meteorological year weather data for the selected location. The DC energy for each hour is calculated from the PV system DC rating and the incident solar radiation and then corrected for the PV cell temperature. The AC energy for each hour is calculated by multiplying the DC energy by the overall DC-to-AC derate factor and adjusted for inverter efficiency as a function of load. Hourly values of AC energy are then summed to calculate monthly and annual AC energy production.

Example 6.4

For this example, use PVWatts and a PV system for Canyon, Texas: 2 kW, 30° fixed tilt, south facing. It displaces electricity at $0.84/kWh. The output for an average year, energy = 3,027 kWh, value of electricity = $256. **Caution:** Actual values may vary from the long-term average by ±30% for monthly values and ±10% for yearly values. The energy production values in the table are valid only for crystalline silicon PV systems.

Find the output from PVWatts program.



AC Energy
&
Cost Savings

Station Identification	
Cell ID:	0208377
State:	Texas
Latitude:	35.0° N
Longitude:	101.9° W
PV System Specifications	
DC Rating:	2.00 kW
DC to AC Derate Factor:	0.770
AC Rating:	1.54 kW
Array Type:	Fixed Tilt
Array Tilt:	30.0°
Array Azimuth:	180.0°
Energy Specifications	
Cost of Electricity:	8.4 ¢/kWh

Results

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	4.83	230	19.43
2	4.92	209	17.65
3	6.04	275	23.23
4	6.56	283	23.91
5	6.35	276	23.31
6	6.60	268	22.64
7	6.69	280	23.65
8	6.25	264	22.30
9	6.05	253	21.37
10	5.92	263	22.22
11	4.85	214	18.08
12	4.41	210	17.74
Year	5.79	3027	255.69

A geographical information system for estimating PV production (PVGIS) is available for Europe, Africa, and Southwest Asia [7]. It is an interactive-map program that calculates solar resource (monthly and average daily radiation) and estimation of PV performance (grid-connected, stand-alone, fixed tilt, and tracking options). Performance for crystalline silicon, CdInSe, CdTe, and others is available. The calculator can suggest the optimum inclination/orientation of the PV modules to obtain maximum yearly production.

6.7 INSTALLED CAPACITY AND PRODUCTION

The installation of PV systems has increased dramatically (Figure 6.12), and the world installed capacity was over 22.9 GW at the end of 2009 [8–10]. Installation in the 1990s was primarily in United States and Japan, then Germany surpassed Japan in 2005; Spain became number two in 2008 (Figure 6.13). The increased installations in the United States [11] are now primarily grid connected: residential, industrial, and utility (Figure 6.14).

Production of PV cells and modules was primarily in the United States, Japan, and Europe in the the 1990s; however, the tigers of Asia have surged in production (Figure 6.15), and in 2009 China led the world with around 2.3 GW of production.

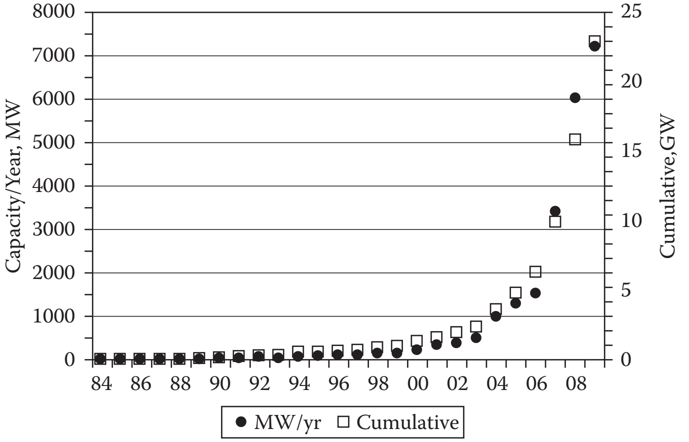


FIGURE 6.12 World PV production per year (MW) and cumulative installation (GW).

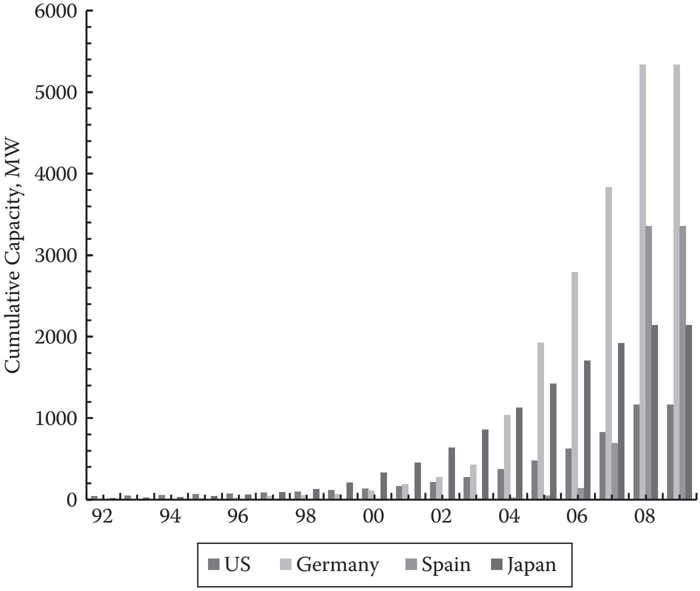


FIGURE 6.13 PV installed capacity (MW) by country.

Shipments of PV cells and modules are divided into three main categories: (1) crystalline silicon cells made from single-crystal or polycrystalline silicon, based on processes such as ingots, cast, and ribbon; (2) thin-film cells made from layers of semiconductor material, such as amorphous silicon (a-Si), cadmium telluride, or copper indium gallium selenide; and (3) concentrator systems, which include reflectors or lenses.

To show how changes in national and even state policies affect events, contrast my future predictions in 2003 for the online course *Solar Energy* with what has actually

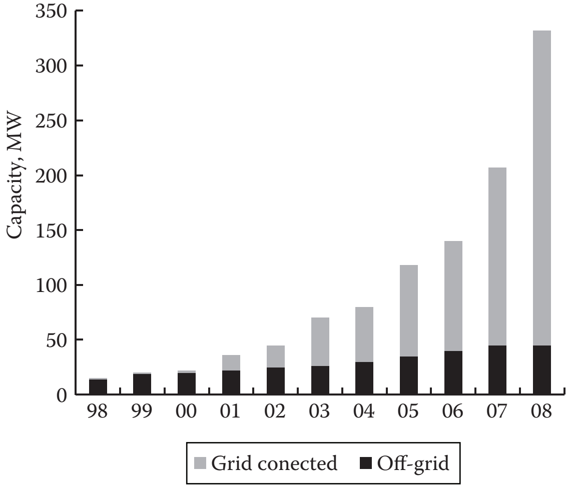


FIGURE 6.14 Yearly PV installed capacity in the United States.

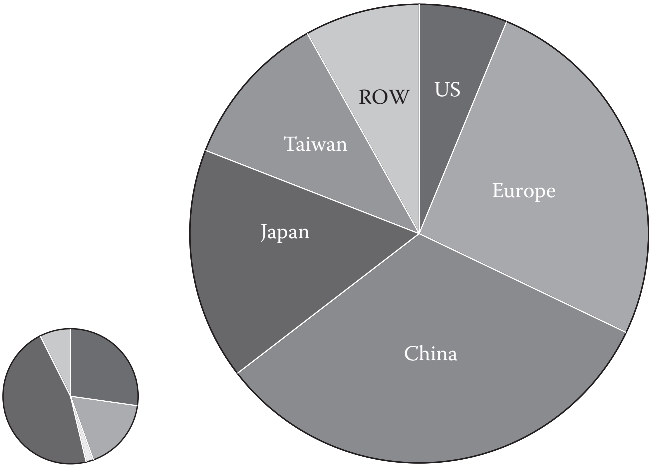


FIGURE 6.15 World PV production (MW) by country: left, in 2000 (world total = 277 MW); right, in 2009 (world total ~7,200 MW). Ratio of the areas is 26/1 (diameter ratio ~ 5/1). ROW = rest of the world.

occurred. My comments were: *production of PV in the world has increased dramatically in the past few years. U.S. is over 80 MW with most of that being exported. Cumulative sales surpassed 400 MW and the forecast is expected to reach 10,000 MW by the year 2030.* Notice that in 2009 the actual world installed capacity was 22,900 MW, and the production of PV was around 7,200 MW (Figure 6.12), which means my predictions based on current information at that time by knowledgeable people were very low. The trend was up, but nobody expected such rapid growth.

Power plants, including PV power plants, can be characterized by rated power (W_P for PV), capacity factor (CF), annual energy production, and of course the installed cost and the cost or value of energy ($/kWh or $/MWh). The (CF) is the average power divided by the rated power, and the average power is usually calculated from energy/time, which is usually for a year.

$$CF = P_{\text{avg}}/P_{\text{rated}} = (\text{Annual energy}/8760)/P_{\text{rated}}$$

6.8 APPLICATIONS

Applications can be divided into the following types:

- Grid connected
  - Residential, industrial, utility-scale power
- Village power (maybe PV alone or hybrid PV with diesel, wind, other sources in parallel)
- Stand-alone
  - Lights, radio, TV, refrigeration, water pumping, water desalinization, water purification
- PV for schools, clinics, local government offices, battery-charging stations.

6.8.1 GRID CONNECTED

In the developed world, as the capacity, size, and number of systems have increased, the major PV type of installation is now grid connected [12]. The advantages of the grid systems are fairly simple connection though an inverter, no storage need, and peak shaving as the PV system produces power primarily when the loads are higher. Today, most PV capacity is installed for grid connection in the developed world, with system size of kilowatts for residential, hundreds of kilowatts for industrial, and megawatts for utility power.

Residential: Size and number of PV systems depend primarily on incentives at the national and even state and local levels. In the United States, the average size for residential systems grew from 2 kW in 2000 to 4.9 kW in 2008. The average size varies by state, depending on available incentives, interconnection standards, net metering regulations, solar resources, retail electricity rates, and other factors.

Japan was a leader in PV production and had a gigawatt of PV installed by 2004, mainly residential [2, Sec. 8.3]. Japan has more homes with PV systems than any other country in the world, with around 60,000 per year being installed. Subsidies for residential systems were phased out by 2006 as the price of PV systems decreased.

Industrial: The average size in the United States has grown to 110 kW_P, and there were 84 systems (30% of capacity) installed with 500 kW and greater in 2008 [13]. In Japan, the prime minister's residence, Japanese Parliament, and many government buildings have 30- to 50-kW PV systems mounted on the rooftops. This is in contrast to the United States where, in the past, President Reagan had a solar system removed from the White House.

Utility Scale: Seventy percent of utility-scale PV plants in Europe are located in Spain (>3.2 GW_P), followed by Germany (~700 MW_P) and Italy (70 MW_P) [14]. Spain has 27 of the top 50 PV plants, ranging from 13 to the largest PV plant in the world (2009) at 60 MW, the Olmedilla Photovoltaic Park (aerial images available on Google). There are four PV power plants of 50 MW and greater (two in Spain and two in Germany), and there is a 46-MW_P (expansion to 62 MW_P under construction) in Portugal. The largest PV plant outside Europe and the United States is a 24-MW_P plant in Korea. As of 2009, the largest utility PV plant in the United States was 25 MW_P, FPL's DeSota Next Solar Energy Center in Florida. Previously, it was the 14-MW_P PV system at Nellis Air Force Base in Nevada.

6.8.2 VILLAGE AND HYBRID POWER

Around $1.6 * 10^9$ people do not have electric service as they are too distant from transmission lines. Extension of the grid is too expensive for most rural areas, and if extended, it has poor cost recovery, which means it is heavily subsidized. Thus, the extension of the grid is too expensive for most rural areas. These people depend on wood, biomass, or dung for cooking and heating purposes; mainly, these materials are collected and cared for by women and girls.

For remote villages and rural industry that have electricity, the standard is diesel generators. Diesel generators are inexpensive to install; however, they are expensive to operate and maintain, and major maintenance is needed from every 2,000 to 20,000 h, depending on the size of the diesel genset. Most small village systems that have diesel power only have electricity in the evening.

Renewable (single or hybrid) village power systems (Figure 6.16) are a minigrid powered by PV, wind, mini- and microhydro, or bioenergy with battery or conventional diesel/gas generators to supply reliable energy (limited). Village power systems can range from small (<100 kWh/day, ~15 kW_P) to large (tens of MWh/day, hundreds of kW_P).

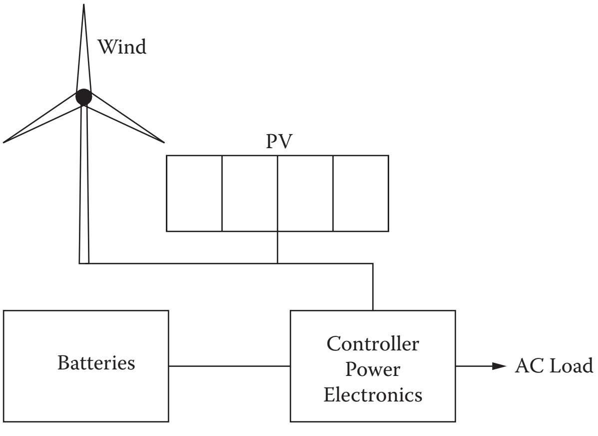


FIGURE 6.16 Diagram of a renewable village power system.

For present village systems powered by diesel generators, the electrical energy is subsidized from the state to national level, and it is difficult to find the actual cost. In general, the costs are \$0.30 to \$0.60/kWh, or even higher for some islands and remote areas. This means that renewable hybrid systems for village power are cost effective today. The problem is the installation of enough village power systems within a region or state that are robust (high reliability) and modular and thus able to reduce the costs by economics of scale and to have the infrastructure for operation and maintenance.

The advantages of village power systems using renewable energy are as follows:

Provide AC or DC power for remote areas. For a system of any size, AC is the standard.
Provide electricity for productive uses.
Modular.
No or low fuel costs.
Lowest life-cycle cost of electricity.
May be owned and operated by local cooperative.

The disadvantages are as follows:

High initial capital cost compared to diesel generators.
More complex: sophisticated controllers, power conditioning, batteries.
High growth in demand means there is not unlimited usage (within a short time, there is the need for load management, load limitation).
Few suppliers, few systems installed; need high-volume production.
Infrastructure: who maintains (trained personnel), how much do consumers pay per kilowatt hour?

Institutional issues are more important than the technical issues, especially for demonstration projects, as many demonstration projects can become political. Institutional issues are as follows:

Planning, which includes locals
Cost, subsidies (who, how much), repairs (maintenance fee or paid at occurence)
Ownership
Operations and maintenance, training of operators
Financing; world (multilaterals), other nation aid agencies (lateral), and non-government organizations; national, state, local, and private organizations
Tariff design, metering, ability and willingness to pay
Load growth, education of users
Quality of service
Economic development versus social services (schools, clinics, local government offices)
Cultural response
Cooperation: local, state, national, electric utilities, financing

FIGURE 6.17 A 50-kW PV array with controller and a large battery bank were added to the diesel station in the village of Campinas, Amazonas, Brazil. (From National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), www.nrel.gov/ncpv.)

The types of village renewable systems are the following:

- Fuel-saver system, addition of renewable energy system to existing diesel power plant (Figure 6.17)
  - Low penetration
  - High penetration, need to control system
- Renewable energy source, single or combination, with battery storage
  - Hybrid system 1: renewable source (single or combination), diesel/gas generators
  - Hybrid system 2: renewable source (single or combination), battery bank, diesel/gas generators

China is the world leader in village power systems [15]. The SDDX program for renewable village power and single-household systems (SHSs) for western provinces of China installed 721 PV/wind systems (15,540 kW), 146 minihydro (113,765 kW), and 15,458 SHSs (1,102 kW).

A major acquisition for any village is television, whether at school, a community center, or even individual households. As an example, a PV system was installed in a village in China, even though the grid was only 10 km away, and the village chief became an entrepreneur as he became the local cable provider.

6.8.3 STAND-ALONE

In the past, the two main applications for PV were (1) small systems, single modules (50 to 100 W) for stand-alone electricity for remote areas; and (2) water pumping for livestock and residences. These are still important applications with the addition of remote and mobile applications for signals and data transmission. More details on

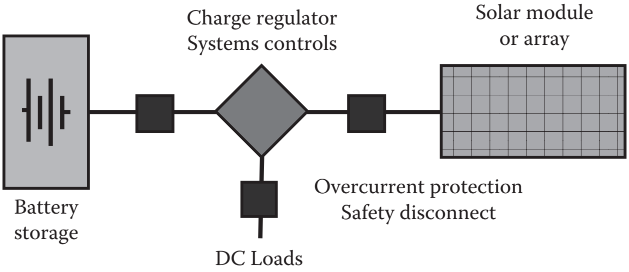


FIGURE 6.18 Diagram of simple PV system for lights, radio, and television.

FIGURE 6.19 PV systems (50 W) for two fluorescent lights, village of Cacimbas in the state of Ceara, Brazil. Notice the tilt angle of the collectors. (From National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), http://www.nrel.gov/ncpv.)

stand-alone PV systems are given in References 2 (see Sec. 8.5–13) and 16. Many PV systems had a single module for lights and a radio, with later installations having larger modules to have enough power for a TV (even color). The system consists of a module, controller, and battery (Figures 6.18 and 6.19).

In remote locations, PV is cost competitive with batteries and even with small diesel generators. Notice that for small power uses, PV is even cost competitive with connection to an adjacent utility power line as PV is used for school crossing lights, flashing stop signs, and so on.

Water pumping for livestock, residences, and villages is important in all regions of the world. Now, tens of thousands of PV water-pumping systems are installed throughout the world. The advantages are the same as for other PV systems: reliability, durability, and no fuel cost. The disadvantage is the high initial cost. Any water-pumping system requires maintenance, no matter the power source.

The standard for water pumping is diesel engines. Depending on the hydraulic power and total power (dynamic head * volume, m–m^3/day) needed, there is a range of pumping systems, from hand pumps to diesel (Figure 6.20). Of course, the PV and

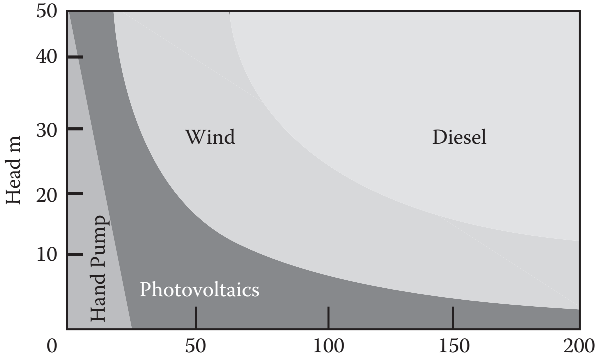


FIGURE 6.20 Competitive ranges for water-pumping systems in terms of hydraulic power (m^4/day).

wind systems depend on the availability of the resource as a good resource makes them more economical. The solar resource should be > 3 kWh/m^2 per day and the wind resource should be an average of 3–4 m/s for the month of highest demand. For small systems, PV is the most economical; for midsize systems, wind is more economical; and for very large systems, diesel is still more economical. PV should be considered when the hydraulic power is from 200 to 1,500 m-m^3/day. One of the good things about water-pumping systems is that storage tanks are fairly cheap, so wind and solar systems can supply water for a number of days. Now, there are some wind/PV hybrid water-pumping systems.

PV systems are now becoming the choice for pumping small amounts of water and even for village systems (Figure 6.21). The farm windmill will only pump around 10 to 20 L/min and will not pump the large volumes needed for a village. PV water-pumping systems can use a direct connection through a controller from the modules or an array to the pump and no batteries. PV water pumping for livestock has replaced many farm windmills in the United States (Figure 6.22), especially as many farm windmills are 30 or more years old, and the trade-off is the difference among repair, a new farm windmill, or a new PV system. PV water pumping is even the economical choice for replacing electric pumps at the end of long utility lines.

UV radiation and ozone can be used for water purification, which can be driven by electricity produced by renewable energy: PV, wind, and PV/wind hybrid [17,18]. Light-emitting diodes, which have long life and low energy requirements, now provide a good source for UV radiation powered by renewable energy [19]. An UV water purifier powered by different configurations of renewable energy was tested [20]: two by PV (100 W), two by wind (500 W), and one by hybrid wind/PV. The PV-only system was more efficient and cost effective than the wind-only system. However, the wind/PV system was more reliable in terms of power. The system purified 16,000 L/day, which is enough potable water for around 4,000 people at an estimated equipment cost of around $5,000. A hybrid system in Afghanistan powered by a 1-kW wind turbine, 280 W of PV, a small battery bank, and an inverter provides

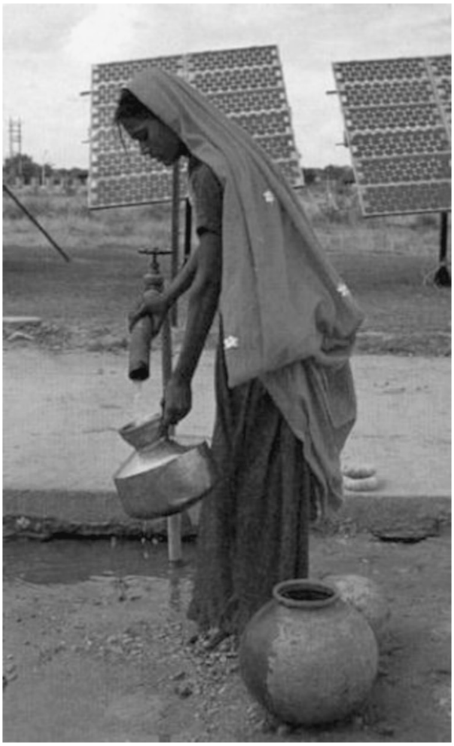


FIGURE 6.21 PV water-pumping system for village in India. (From National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), http://www.nrel.gov/ncpv.)

FIGURE 6.22 PV with passive tracker for pumping water for livestock. (From National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), http://www.nrel.gov/ncpv.)

around 160 W to generate 2 g/hr of ozone [21]. The ozone is used to treat 500 L of water at a time (batch process), and most communities using the system treat about 2,000 to 4,000 L/day.

6.9 COMMENTS

An intriguing development is transparent PV collectors that generate electricity from UV radiation and allow visible light to pass through. A company makes glass containing dyes that concentrate and deflect solar energy to PV cells, so frames of windows and skylights could become producers of electricity that are integrated into a building.

The growth of installed PV has been dramatic and will continue to grow due to national and state policies, especially in reaction to global warming. This means that the costs will continue to decrease from residential to utility-scale systems. Inverters with individual panels, more efficient PV materials, flexible PV membranes [22], integrated PV with buildings (e.g., PV shingles or rooftops), and other technical advances mean PV has a bright future.

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RECOMMENDED RESOURCES

LINKS

Enerank. Energy ranking. http://www.enerank.com/index.php.

National Center for Photovoltaics, NREL. http://www.nrel.gov/ncpv.

Photos of PV and village systems available from NREL, Photographic Information eXchange. http://www.nrel.gov/data/pix/.

Photovoltaics, Solar Energy Technologies Program, EERE, DOE. http://www1.eere.energy.gov/solar/photovoltaics_program.html.

PV Resource. http://www.pvresources.com.

Sandia Labs. http://www.sandia.gov/pv/main.html.

Solar Electric Power Association. http://www.solarelectricpower.org.

Solar Energy Industries Association. http://www.seia.org.

PROBLEMS

1. List two advantages and two disadvantages of PV systems.
2. The peak of solar intensity is in the yellow region (see Figure 3.5). What is the energy of photons of yellow light in electron volts if the yellow light has a frequency of $5 * 10^{14}$ Hz and a wavelength of $6 * 10^{-7}$ m?
3. Pick any manufacturer and one of their solar modules. Find specifications for rated power, voltage, and current at rated power. Be sure to state manufacturer and module number.
4. BP solar, SX 3200, 200 W_P. If voltage at $P_{max} = 24.5$ V, what is the current? Will that be larger or smaller than the short-circuit current?
5. An array (fixed tilt at latitude) of six modules, each 250 W_P, is connected to the grid through an inverter. What is the average power from the system? Show steps or reasoning.

6. An array (fixed tilt at latitude) of six modules, each 250 W_P, is connected to the grid through an inverter. Estimate annual energy output for Amarillo, Texas.
7. The largest PV plant in the world, 60 MW, is in Spain. There are 1,700 annual average sun hours. Estimate the annual energy output.
8. You want an average of 600 kWh/month for a home near Denver, Colorado. How big (power) a PV system should you buy? How much area is needed for the array? Use crystalline silicon modules.
9. You want an average of 600 kWh/month for a home near Denver, Colorado. How big (power) a PV system should you buy? How much area is needed for the array? Use amorphous silicon modules.
10. How much more energy can be obtained from a flat-plate PV system with one-axis tracking?
11. Use the PVWatts calculator. What is the estimated annual energy for a 4-kW PV system (fixed tilt at latitude –15°) for Phoenix, Arizona?
12. Use the PVGIS for Casablanca in northern Africa. What is the estimated annual energy for a 4-kW PV system (fixed tilt at latitude)?
13. What is the average-day kilowatt hour per square meter for Roswell, New Mexico, for a PV system at fixed tilt at latitude –15°? For a 50-MW utility plant and crystalline silicon modules, what is the approximate area of the array?
14. Estimate the CF for a 50-MW PV utility plant located in area with an average of 4.7 sun hours/day for a fixed-plate system tilted at latitude.
15. Why have grid-connected systems taken much of the market in the world?
16. In the United States, what is the approximate size of the PV market (MW/yr) for the following: residential, industrial, and utility scale? Estimate the size of the market for 2020.
17. What would you consider as the three major institutional issues for village power? Give reasons for your answers.
18. From the Web, find any example or case history of PV water pumping. Then, write down system parameters and output (if given).
19. To consider PV water pumping as an option, what is the approximate range of hydraulic power?
20. Contrast water purification by UV radiation or ozone using PV power. Which treatment would you use? Why?
21. Find any commercial water purification unit that uses renewable energy for power. List specifications for power and average production.

7 Concentrating Solar Power

7.1 INTRODUCTION

The most common collectors are flat-plate collectors for space and water heating. It is possible to get higher temperatures for process heat and for solar cooling with well-insulated flat-plate collectors with two to three glazings; however, most higher-temperature collectors use some form of concentration for thermal generation of electricity, cooling (absorption cooling), or process heat [1]. Concentrating collectors can also reduce the amount of photovoltaic (PV) cell area for producing electricity. Concentrating solar power (CSP) requires direct radiation, so these collectors need to be in areas with a good-to-excellent solar resource (2,000 to 3,000 kWh/m^2/yr or an average of 5.5–8 sun hours/day. See solar maps in Chapter 3 for those regions of the world with that solar resource, which are primarily deserts and arid regions.

Even though it is not a conventional CSP, solar ponds can be used to generate electricity in the same manner. The collector is the pond, and the salt gradient allows for stratification of the thermal energy, which can be used to drive the turbine to generate electricity.

CSP systems can provide firm or peak power or even base load capacity due to thermal storage or fuel backup; they produce the greatest amounts of power during the afternoon when electricity demand is high. The main types of solar thermal generation of electricity are power tower, line or linear focus, and dish/engine.

Power tower, point focus
  Heliostat (parabolic shape or smaller individual mirrors to approximate parabolic shape)
  Two-axis tracking
  Focal length about hundreds of meters
  Concentrating ratio about 800
Line or linear focus
  Parabolic two-dimensional (2D) shape or linear Fresnel
  One-axis tracking, east to west
  Focal length about 3 m
  Concentrating ratio about 30–40
Dish, point focus
  Parabolic three-dimensional (3D) shape
  Two-axis tracking
  Focal length about 1–4 m
  Concentrating ratio about 3,000

The power tower uses tracking mirrors (heliostats) to focus sunlight onto a boiler located on a tower (power tower); line focus uses parabolic troughs or Fresnel lenses to focus on a linear collector tube (receiver); the dish/engine uses a parabolic dish and a receiver at the focal point, and a number of Fresnel lenses can be used to focus sunlight on PV cells. The CSP collectors can use one- and two-axis tracking (Section 6.6.2). In both systems, there are operation and maintenance problems with the control and operation of motors and gears and the match between materials for thermal expansion at rotating joints. Heliostats are two-axis reflectors; most parabolic troughs use one-axis tracking. Some systems use tracking systems and concentrators to focus sunlight onto small PV cells, either line focus or point focus with individual units.

CSP projects are listed by country, project name, technology, and status [1]. Also, overviews are available for four technologies: power tower, parabolic trough, linear Fresnel reflectors, and dish/engine. Sandia Laboratories has a searchable database for CSP projects [2]; it includes images.

7.2 POWER TOWER

Scientists in Russia first proposed the power tower concept in the mid-1950s, and after the oil crisis of 1973, a number of experimental systems were built in various countries [3]. A power tower system uses a large field of heliostats to focus and concentrate the sunlight onto a receiver on the top of a tower (Figure 7.1). The concentrated beam has very high energy; a bird flying into the beam would be vaporized. A heat transfer fluid is used to generate steam for a conventional electric generator. The heat transfer fluid could be water or steam or molten salt because of its superior heat transfer and energy storage capabilities. Thermal storage allows the system to continue to dispatch electricity during cloudy weather or at night, and with the addition of fossil fuel, the system can provide firm or base power.

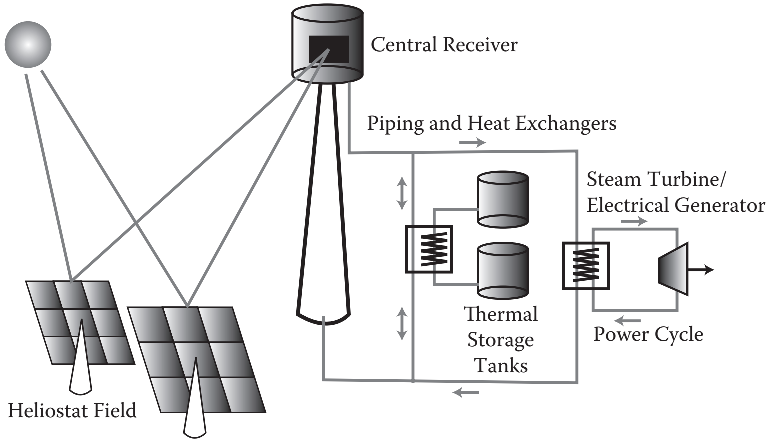

FIGURE 7.1 Diagram of power tower for generating electricity. (From Sandia Labs.)

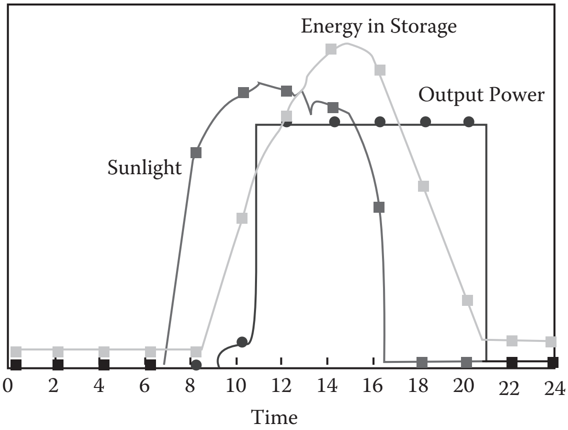

FIGURE 7.2 CSP input, storage, and output power for a winter day. (From Sandia Labs.)

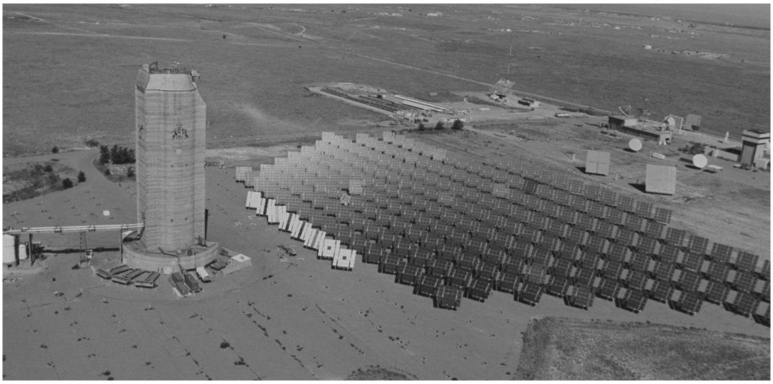

FIGURE 7.3 Sandia central receiver thermal test facility. (From Sandia Labs.)

The annual capacity factor of most solar technologies without storage is around 25%; however, with the addition of thermal storage, power towers can have annual capacity factors of up to 60% and as high as 80% in the summer. There are enough heliostats to provide sufficient energy to power the turbine and provide the extra energy for storage. At night or during extended cloudy periods, the turbine is powered with the stored thermal energy (Figure 7.2). In Figure 7.2, sunrise was around 0730, and the intensity of sunlight rose rapidly then dropped off before sunset after 1630. Notice that power output was started at 1100, when it was needed by the utility.

In 1976, an experimental power tower was constructed at Sandia National Laboratories with a field of over 200 heliostats. It is now the central receiver test facility (Figure 7.3) with 5 MW of thermal power and a peak flux of 260 W/cm^2. Then, Solar One, a 10-MW demonstration project was constructed near Barstow, California, that had 1,818 heliostats, each 40 m^2. During operation from 1982 to 1988, it produced around 38 million kWh. In 1995, Solar Two (Figure 7.4) was a retrofit to Solar One to demonstrate the advantage of molten salt over water or steam for heat transfer and

FIGURE 7.4 Solar Two, Barstow, California. Notice receiver, which is white hot, and the oil storage tanks at the bottom. (From Sandia Labs.)

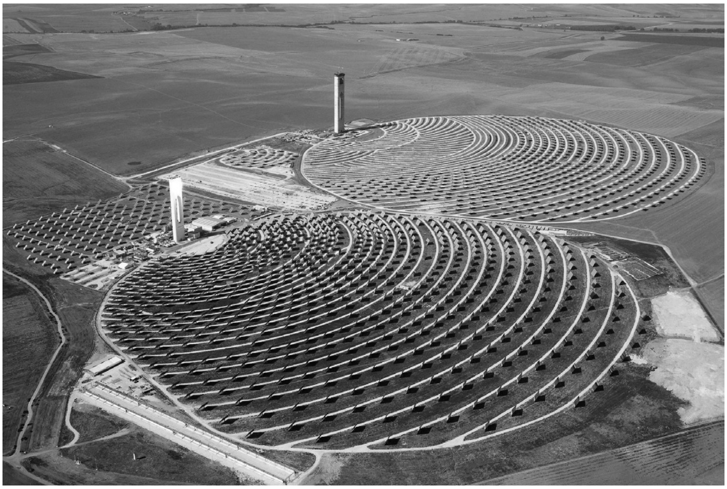

FIGURE 7.5 Abengoa power towers, Seville, Spain. Top is 11 MW, bottom is 20 MW. Notice that there are also PV panels. (Courtesy of Abengoa.)

storage. A second ring of 108 larger 95-m^2 heliostats was added, for a total of 1,926 heliostats with an area of 82,750 m^2. Solar Two was decommissioned in 1999 due to economics and in 2001 was converted by the University of California, Davis, into an air Cherenkov telescope, measuring gamma rays hitting the atmosphere.

There has been renewed interest in power towers with the construction of 11- and 20-MW plants in Spain (Figure 7.5). For the 11-MW plant, there are 624 heliostats, each 120 m^2, to focus sunlight onto the 115 m tall central receiver. There is 1 h of storage of pressurized steam, 50 bar at 285°C. For the 20-MW plant, there are

1,255 heliostats, each 120 m^2, covering an area of 95 ha (235 acres), and the central receiver is on a 160-m tower. Another power tower, Gemsolar, of 17 MW is being constructed in Spain.

7.3 LINE OR LINEAR

The line focus collectors use parabolic troughs, reflecting mirrors, or linear Fresnel reflectors. Generally, the line focus system is oriented in the north-south direction, with one axis tracking in the east-west direction (Figure 7.6). Focus is by a parabolic trough (Figure 7.7) or linear Fresnel reflectors (Figure 7.8). A Fresnel lens takes the continuous surface of a standard lens into a set of surfaces of the same

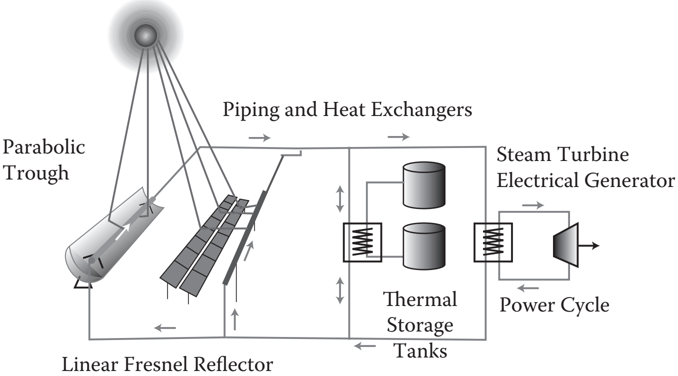

FIGURE 7.6 Diagram of line focus, parabolic trough or Fresnel lens, for generating electricity. (From Sandia Labs.)

FIGURE 7.7 Parabolic troughs at Solar Energy Generating Systems, 345 MW. (From Sandia Labs.)

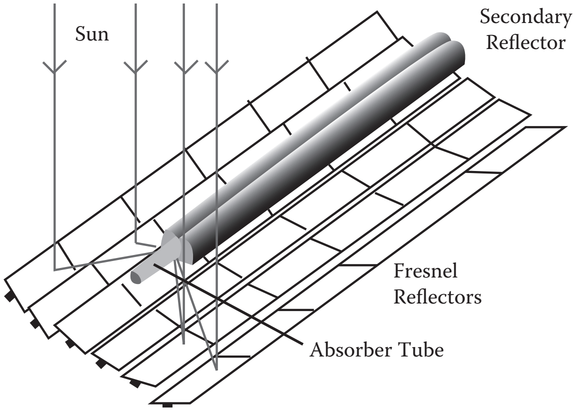

FIGURE 7.8 Diagram of linear Fresnel reflector system. Notice secondary reflector on top of receiver tube.

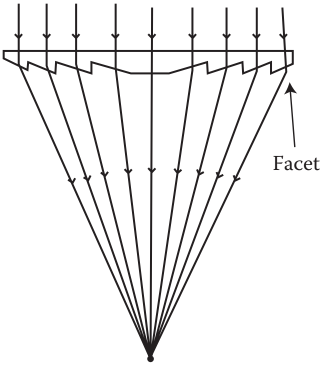

FIGURE 7.9 Diagram of Fresnel lens.

curvature (Figure 7.9), with discontinuities between them, thus reducing thickness and weight. For solar applications, they can be formed from plastic or glass. The typical heat transfer fluid is a synthetic oil heated to around 390°C, and electricity is generated in a conventional Rankine cycle steam turbine. The oil can also be used for heat storage.

There were around 620 MW of parabolic troughs installed in the world through 2009, with 420 MW in the United States (Table 7.1) and 200 MW in Spain. The early systems (installed in 1985–1991 and still operating) were the Solar Energy Generating Systems (SEGS) in Southern California. There are a number of 50-MW plants under construction in Spain (1,150 MW), and there are large plants under construction in Algeria (150 MW) and in Morocco (450 MW).

There are two linear Fresnel reflector plants in operation (in 2009): the Kimberlina 5-MW plant (Figure 7.10) near Bakersfield, California, and a 1.4-MW plant near Calasparra, Spain. The steel-backed mirrors are located near the ground and rotate individually while focusing on the fixed receiver tube (Figure 7.11), in contrast to the

TABLE 7.1
U.S. Parabolic Trough Systems

Plant	Location	Year	MWe	Temperature Out °C	Area, m²	Efficiency, %	Power Cycle	Dispatch
SEGS I	Daggett, CA	1985	13.8	307	82,960	31.5	40 bar, steam	3-h TES
SEGS II	Daggett, CA	1986	30	316	190,338	29.4	40 bar, steam	Gas boiler
SEGS III	Kramer Junction, CA	1987	30	349	230,300	30.6	40 bar, steam	Gas boiler
SEGS IV	Kramer Junction, CA	1987	30	349	230,300	30.6	40 bar, steam	Gas boiler
SEGS V	Kramer Junction, CA	1988	30	349	250,500	30.6	40 bar, steam	Gas boiler
SEGS VII	Kramer Junction, CA	1989	30	390	194,280	37.5	100 bar, reheat	Gas boiler
SEGS VI	Kramer Junction, CA	1989	30	390	188,000	37.5	100 bar, reheat	Gas boiler
SEGS VIII	Harper Lake, CA	1990	80	390	464,340	37.6	100 bar, reheat	HTF heater
SEGS IX	Harper Lake, CA	1991	80	390	483,960	37.6	100 bar, reheat	HTF heater
APS Saguaro	Tucson, AZ	2006	1	300	10,340	20.7	ORC	None
Nevada Solar One	Boulder City, NV	2007	64	390	357,200	37.6	100 bar, reheat	None

SEGS = Solar Energy Generating Systems; HTF = heat transfer fluid; ORC = organic Rankine cycle; TES = thermal energy storage.

FIGURE 7.10 Linear Fresnel reflector, Kimberlina plant, 5 MW. (Courtesy of Ausra.)

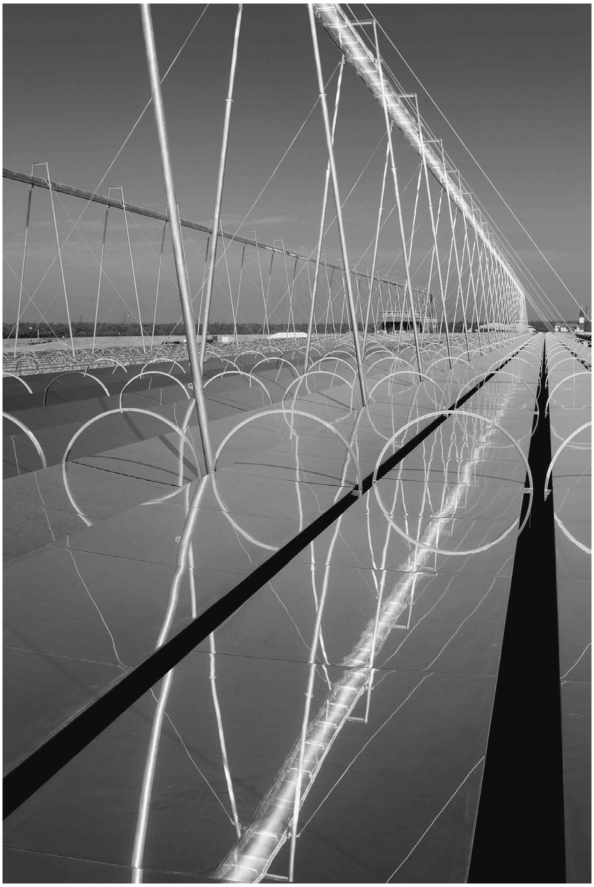

FIGURE 7.11 Close-up of mirrors (each 2 m wide) and receiver tube, which is 18 m above ground, Kimberlina plant. (From Sandia Labs.)

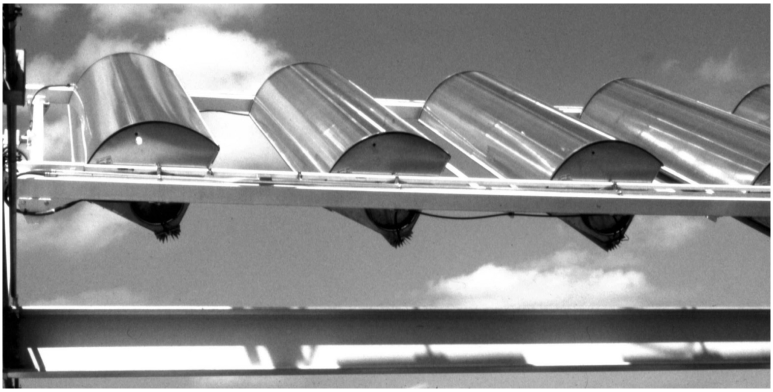

FIGURE 7.12 Linear Fresnel lens, PV strip (4 cm wide) at focus, two-axis tracking, system (around 400 W per unit), 300-kW array, at 3M Research Center in Austin, Texas (1990). Notice fins on the back for heat dissipation.

parabolic troughs where the receiver tube moves with the trough. The Kimberlina plant has the following configuration:

26,000-m^2 solar field aperture area
Three 385-m lines
Ten 2-m wide mirrors
Fixed 18-m high receiver
Water transfer fluid
40-bar power cycle pressure

Of course, the same system could be used for auxiliary steam for existing power plants or for process heat.

Some systems use tracking systems and concentrators to focus sunlight onto a line of PV cells (Figure 7.12), thereby reducing the PV cell area. Since a PV system decreases in efficiency with higher temperature, the extra heat needs to be used or dissipated. The same type of units provided 24 kW electricity for the Dallas–Fort Worth airport and 140 kW of thermal energy for its Hyatt Hotel.

7.4 DISH/ENGINE

A dish/engine system uses a mirrored parabolic dish for focus on a thermal receiver, which transfers heat to the engine/generator. The parabolic shape is generally made from individual mirrors or reflecting membranes. The most common type of heat engine is the Stirling engine, which uses the fluid heated by the receiver to move pistons and create mechanical power to run a generator or alternator. Stirling engines [4] depend on expansion and compression at different temperatures of a gaseous working fluid; the external heat can be from any source. Remember that conventional

FIGURE 7.13 Test field for dish/engine at Sandia National Laboratories. (Courtesy of Sandia Labs.)

FIGURE 7.14 Suncatcher at Sandia test field. (From Sandia Labs.)

thermal generation of electricity requires cooling, generally by water; however, the Stirling engine does not require much water.

Sandia Labs has worked on experimental dish/engines for a number of years and has a test bed of six systems (Figure 7.13) with a power output of 150 kW. The latest configuration, 25 kW, is round (Figure 7.14) and reached an efficiency of 31%, sunlight to electricity. A unique experimental system was built at Crosbyton, Texas, where the collector (spherical dish with mirrors) was fixed, and the line focus was movable.

A demonstration project used dishes for higher temperatures for process heat and air conditioning (Figure 7.15). Another demonstration dish system was a combined heat system, 400 kW of electricity and 150 tons of chilled water, that was installed in 1983; however, it only operated for 4 yr.

FIGURE 7.15 Solar Total Energy System, 144 dishes, 7 m diameter, at textile plant near Shenandoah, Georgia. The dishes provided thermal energy for process heat and air conditioning at a nearby textile mill. (From National Center for Photovoltaics, NREL, http://www.nrel.gov/ncpv.)

7.5 POINT FOCUS

Other CSP systems with two tracking systems use individual Fresnel lenses to reduce the amount of PV material (Figure 7.16). One company has installed around 13 MW of high-concentration PV [5]. Another similar system is the compound parabolic reflector (Figure 7.17).

In 1995, West Texas Utilities built a solar energy demonstration project at the end of a feeder line near Fort Davis, Texas. The project consisted of the following systems:

PV, 83-kW systems, line focus, Fresnel lenses, two axis, (similar to Figure 7.12)
PV, 20 kW, flat with multiple Fresnel lenses, two axis (similar to Figure 7.16)
Dish/Stirling engine, 7 kW, multiple mirrors, stretched membrane, two axis
PV array, 100 kW, flat-plate panels, one axis

The dish was installed but Cummins never delivered the Stirling engine, and within a few months dropped that business. Because of high operation and maintenance costs, the rest of the project was dismantled by 2000.

7.6 SOLAR POND

A solar pond is not really a concentrating solar system; however, the production of electricity is similar to other renewable energy systems that use a Rankine turbine. The major differences are that the collector and storage are together, and there is a small temperature differential between the stratified layers. A solar pond consists of a salinity gradient to trap the heat (Figure 7.18), which can then be used for generation of electricity, process heat, and freshwater. The temperature of the bottom layer is around 90°C, while the temperature of the top layer is around ambient temperature,

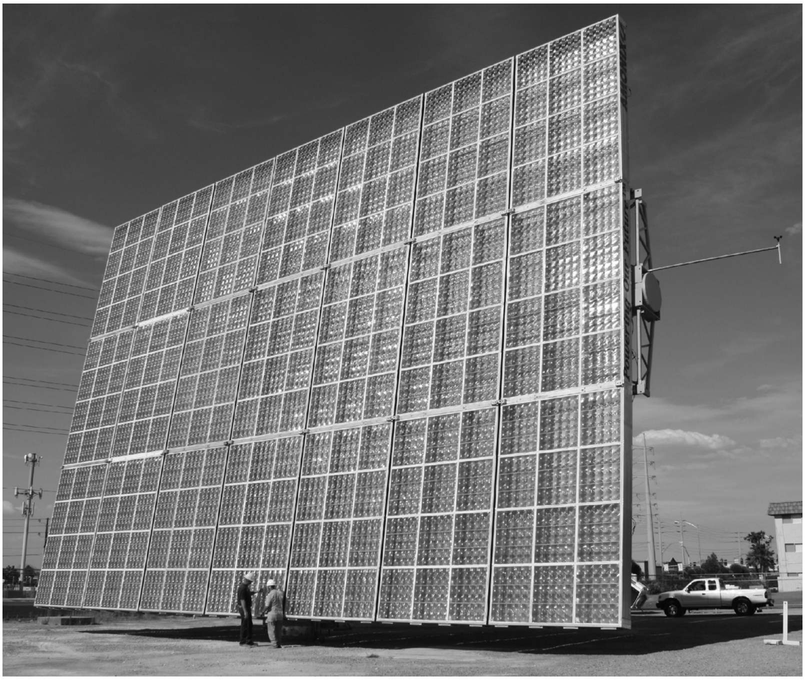

FIGURE 7.16 Fresnel lenses, point focus, 53 kW, two-axis tracking, 22 m wide by 15 m high collector area. (Courtesy of Amonix.)

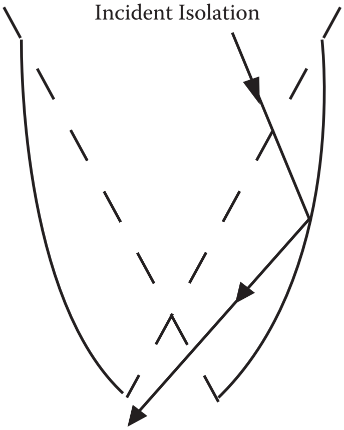

FIGURE 7.17 Compound parabolic reflector.

30°C. A 250,000-m^2 solar pond for generation of electricity (5 MW) was constructed on the Dead Sea in Israel and operated until 1988 [6].

The El Paso solar pond (Figure 7.19) was a research and demonstration project of the University of Texas at El Paso started in 1984. In addition to the R&D aspect, process heat was provided for Bruce Foods, a canning company located adjacent to

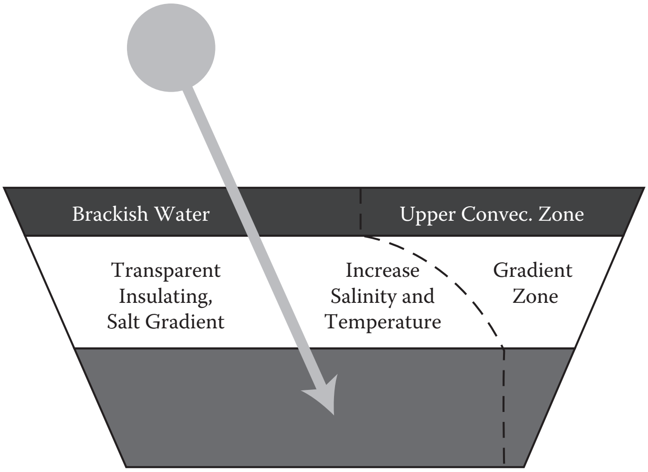

FIGURE 7.18 Diagram of salt gradient solar pond.

FIGURE 7.19 El Paso solar pond; notice wave suppression devices.

the solar pond. In 1986, the project was expanded to produce electricity (Figure 7.20). The solar pond, with 300-kW thermal capacity, had a Rankine cycle engine with a 100-kW generator that was grid connected. The surface area of the pond was 3,350 m^2, and it was 3 m deep. During one cold period, the top of the pond froze; however, it still produced some power. As expected, maintaining a proper gradient with little or no mixing between layers and evaporation are major problems. Wave suppression devices on the top of the pond were installed to reduce mixing. A membrane failure shut the plant down for three years, 1992–1995, and then it was closed in 2003 due to economics.

FIGURE 7.20 El Paso solar pond with Rankine-cycle engine (100 kW) for electric generation in the foreground.

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6. C. Nielson, A. Akbarzedeh, J. Andrews, H. R. Becerra L., and P. Golding. 2005. The history of solar pond science and technology. *Proceedings of the 2005 International Solar Energy Conference*, Orlando, FL.

RECOMMENDED RESOURCES

LINKS

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Concentrating solar power, energy from mirrors. 2001. http://www.nrel.gov/docs/fy01osti/28751.pdf.

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Solar Pace. Pdfs on technology. http://www.solarpaces.org/CSP_Technology/csp_technology.htm; http://www.solarpaces.org/CSP_Technology/docs/solar_dish.pdf; http://www.solarpaces.org/CSP_Technology/docs/solar_tower.pdf (1997); http://www.solarpaces.org/CSP_Technology/docs/solar_trough.pdf; http://www.solarpaces.org/CSP_Technology/docs/solarpaces_fresnel_9_2002.pdf.

Solar ponds. http://www.solarponds.com.

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TroughNet. Parabolic trough solar power network. http://www.nrel.gov/csp/troughnet/.

MORE TECHNICAL INFORMATION

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W. B. Stine and M. Geyer. 2001. *Power from the sun*. Power from the SUN.net. http://www.powerfromthesun.net/book.htm.

PROBLEMS

1. For the year with the latest data available, how many megawatts of power tower were installed in the world?
2. For the year with the latest data available, how many megawatts of linear CSP were installed in the world?
3. For the year with the latest data available, how many megawatts of dish, point focus CSP were installed in the world?
4. What are the advantages and disadvantages of using CSP to produce electricity?
5. For the parabolic trough, SEGS, California, what are the total megawatts installed? What are the estimated kilowatt hours/year produced?
6. What is the capacity factor for SEGS, California?
7. What is the estimated capacity factor for PS20 in Spain?
8. Reference 1 lists CSP projects by country. List the first five countries and megawatts installed.
9. What are average efficiencies, sun energy to electricity, for a power tower? For a linear parabolic trough?
10. What is the average efficiency, sun energy to electricity, for a dish/engine?
11. Why are Fresnel lenses used for CSP?
12. Why was Solar Two shut down?
13. Why would CSP be used with PV?
14. Contrast efficiency and cost between flat-plate PV and CSP PV.
15. What is the advantage of the dish and Stirling engine for producing electricity rather than the dish and thermal generation of electricity?
16. In a good solar regime, estimate annual kilowatt hours for a one-unit dish/engine for Stirling Energy Systems. Be sure to include the collector area of the unit.
17. In a good solar regime, estimate the annual kilowatt hours for one-unit point focus at Amonix. Be sure to include the collector area of the unit.
18. Dishes were used for process heat. Are there any such systems on the commercial market today?
19. Are there any operating solar ponds in the world today? Go to the Internet and briefly describe one project. If you cannot find a current project, describe a past project.
20. Calculate the maximum theoretical efficiency for a solar pond.
21. Calculate the maximum theoretical efficiency for a power tower.
22. Calculate the maximum theoretical efficiency for a parabolic trough system.
23. What is the status of the Maricopa Solar dish/engine plant? What are the megawatts, number of units, rated power per unit, and operational status?
24. What is the area/megawatt needed for a power tower linear system with a dish/engine? For a power tower and linear system, you need to include the steam turbine and storage area.

8 Solar Systems

8.1 INTRODUCTION

The design of solar systems is based on engineering (use of math), architecture, and research by scientists. The design then is reduced to guidelines for builders, contractors, homeowners, and so on. Of course, if you have an architect, the architect will do an integrated design with detailed plans for you. Today, many of the applications are in terms of computer simulations and spreadsheets. Generally, the structure combines one or more systems.

Finally, if you want to design, build, implement, or do it yourself, there is a lot of information available. A number of homes with one or more renewable energy systems have been constructed in all regions of the United States. The Southwest probably has more passive solar homes (Figure 8.1) and buildings than other regions of the country. Most people are receptive to sharing and even showing their solar or renewable energy systems. Be sure to ask about performance and any difficulties or problems they have with their renewable energy systems. In any case, passive solar homes or renewable energy systems need to be designed and sized for the local climate. This chapter is primarily for description of homes, including underground homes since most have a south-facing side that has windows for direct gain. Finally, there are homes that are completely self-sufficient, off the grid. You can obtain information on solar home tours by state from the American Solar Energy Association (http://www.nationalsolartour.org) or from state solar organizations. For example, the Northern California Solar Energy Association has information on education and systems (http://www.norcalsolar.org).

FIGURE 8.1 Passive solar home with direct gain; Trombe walls and large thermal mass provide most heating needs of an adobe home in Santa Fe, New Mexico. (From EERE, http://www.eere.energy.gov.)

8.2 PASSIVE SYSTEMS

If you want to design and construct your own passive system or do most of the work, the following are excellent sources: Passive Solar Home Design Checklist, www.ncsc.ncsu.edu/fact/22body.htm and Edward Mazria's, *The Passive Solar Energy Book* [1], The 27 patterns in *The Passive Solar Energy Book* provide more detailed information on design and sizing of components.

The following information is for those locations in the world with sufficient sun for heating during the winter and different techniques for cooling during the summer. Directions for north and south should be interchanged for the southern hemisphere and shading of windows in the equatorial zone has to be on both the north and south. There are three main components for a passive solar energy home: reduction or small heat loss in the winter and reduction or small heat gain in the summer (well insulated home), sunlight to enter space for heating in the winter and for daylighting all year, and thermal mass to reduce heat fluctuations on daily basis and 3 to 5 days with no sunlight. The thermal mass can also be used for keeping the house cool in the summer.

Indoor temperature in a passive solar home may fluctuate from 6 to 15°C and the amount of fluctuation is a function of the amount of building insulation (rate of heat loss); location, size, and type of windows; amount of thermal mass; and the color of the interior surfaces. The solar heating cannot be turned on or off (unless you have moveable shutters and shades) and there is little control of the flow of heat inside the home. To prevent overheating, shading is used to reduce solar gain in summer, or excess heat is vented through open windows or by an exhaust fan. Most passive solar homes will have an auxiliary heat source to help reduce temperature fluctuations and to provide heat for long periods of overcast days. However the size of an auxiliary heating system can be smaller due to the passive components than the size needed for the same floor area of conventional home.

Different systems, for example direct gain, indirect gain, clerestory, skylights, Trombe wall, sunroom, have different design limitations, so one or a combination of systems can be used. Choose a system or systems that satisfies most of the heating and/or cooling requirements of each space. Examples and designs of passive solar homes are available in the literature and the Internet.

8.2.1 Location, Orientation, Shape

Place building on the site or lot that receives sunlight from 9:00 in the morning to 3 to 4:00 in the afternoon during the heating season. Remember there is the possibility of shading from future growth of trees or even buildings on adjacent lots. The simplest shape for the building is a rectangle, with the long side on an east-west axis. This long axis can be up to 15 to 20 degrees off of the east-west axis. If you need more heating earlier in the day, you would orient the building toward the northeast.

Reduce heat loss by having the north side slope toward the ground, by berms, or by building into the side of a south-facing slope. Reduce heat gain through the west side of the building from the late afternoon sun during the summer. This can be accomplished through small windows, external shading by deciduous trees, or even some type of shutters.

8.2.2 INDOOR SPACE

Those spaces that are occupied or used the most during the day, for example the living room, should be placed along the south face of the building to receive sunlight, which provides heat and daylighting. Other rooms can be placed to the southeast and southwest, for example bedrooms. Spaces with minimal heating and lighting requirements, for example, closets, garages, and laundry rooms, should be placed along the north face of the building. However laundry rooms need heat in the winter to protect water pipes from freezing.

To reduce heat loss and/or heat gain, the main entrance could be a vestibule or foyer to provide a double entry or air space. Entrance should be located away from prevailing winter winds or shaded to reduce wind velocity. Entrance area can also be a storage space for coats, etc.

8.2.3 WINDOWS

Major windows to let in sunlight will be located on the south face, with possible additional major windows on the southeast and southwest according to the internal requirements of each space. On the west and the north side of the building, window area should be small. In most cases, windows should be double pane or double pane, low-e. Some designs used recessed windows on the north to reduce heat loss in the winter due to wind velocity. Once again, remember large windows on the west let in too much heat during the late afternoon in the summer. A number of houses with the front facing west have aluminum foil placed on the inside of those windows during the summer. Just because the road runs north-south, the long axis of a passive solar home should not be oriented along a north-south axis.

In cold climates (average winter temperatures of –7 to 0°C), the south window area should be between 0.2 and 0.4 m^2 for each one m^2 of floor area. In temperate climates (average winter temperatures of 2 to 7°C), the south window area should be between 0.12 to 0.26 m^2 for each one m^2 of floor area. With sufficient thermal mass, this will let in enough solar radiation during most of the winter to keep the interior of the building at an average temperature of 18 to 24°C. In most cases, use the larger number for window area to reduce daily fluctuations of temperature and to have enough stored energy for 3 to 5 days of overcast skies.

8.2.4 DIRECT GAIN

The most common system, especially for the south walls, is direct gain and it will provide 30 to 75% of the heat in the winter. That means in the spring and fall it could provide all the heat needed. All the south wall could be windows; however, in general that would not be a good design as it would provide too much heat (some sunrooms overheat) and would have a higher heat loss at night, and then there is the cost differential of windows versus insulated wall. Design must include interior surfaces with colors to eliminate or reduce glare.

To retrofit an existing building with a direct gain system is difficult, unless the building has a clear southern exposure and has some thermal mass or it is fairly easy to increase the thermal mass (see example 8.2). One way to increase thermal mass is to use water storage; however, water storage has some potential problems, primarily freezing and leaks.

8.2.5 THERMAL MASS

The thermal mass for the storage of solar heat can be in the interior walls and floors constructed of masonry materials (minimum of 10 cm thickness; however, 20 cm is preferred for less temperature fluctuations and for 3 to 5 days storage during overcast days). For a direct gain system, to reduce glare and store the heat, the direct sunlight can be diffused over the surface area by using a translucent glazing material, by a number of small windows that admit sunlight in patches, or by reflecting direct sunlight off a light-colored interior surface onto other surfaces. For the thermal mass use a medium-dark color for masonry floors, any color for masonry walls, light color for construction of little thermal mass, and do not cover the thermal mass floors with insulation (carpets). However some small rugs may be all right as long as most of the sunlight is being absorbed. If interior water storage is used, than lightweight construction can be used for walls and floors.

Mazria [1] gives three case studies for thermal mass with direct gain system.

> Case 1. A dark-colored concrete mass is placed against the rear wall or in the floor in direct sunlight. The surface area of the concrete exposed to direct sunlight over the day is 1.5 times the area of the glazing. Space temperature fluctuation during the day was about 40°F. (p. 137)
>
> Case 2. A dark-colored concrete mass is placed against the rear wall or in the floor in direct sunlight. An increase in masonry thickness beyond 8 in. results in little change in system performance. The surface area of the concrete exposed to direct sunlight over the day is 3 times the area of the glazing. The temperature fluctuation during the day is 25°F. (p. 138)
>
> Case 3. The entire space walls and floor becomes the thermal mass. The surface area of concrete exposed to direct sunlight is 9 times the area of the glazing. Sunlight strikes a white surface first and then diffuses over the entire space. An increase in masonry thickness beyond 4 in. results in little change in system performance. The temperature fluctuation during the day is 13°F. (p. 139)

An interior water wall for heat storage for a direct gain system should be located so that it receives direct sunlight from south facing windows. The surface of the container exposed to direct sunlight should be a dark color, at least 60% solar absorption. Use around 300 liters of water for each one m^2 of window area. The Alternative

Energy Institute had some water storage tubes (see Figure 8.5), however top covering was not good, food dye stratified, and tubes collected dust.

Thermal mass for an indirect gain system (glazing, storage wall, and then living space) could be a Trombe wall or a water wall (see Section 5.4.2). The system would be south facing, double-glazed and thermal storage (masonry or water). In cold climates (average winter temperatures of –7 to 0°C), the south glazing area should be between 0.4 and 1.0 m^2 for one m^2 of floor area for masonry wall and 0.3 and 0.8 m^2 for one m^2 of floor area for water wall. In temperate climates (average winter temperatures of 2 to 7°C), the south glazing area should be between 0.22 and 0.6 m^2 for one m^2 of floor area for masonry wall and between 0.16 and 0.43 m^2 for one m^2 of floor area for water wall. The outside face of the wall should be a dark color. In cold climates, vents (see Figure 5.8) are placed at the top and bottom of a masonry wall to increase the system performance. The ratio of the area of each row of vents to the wall area should be approximately 1 to 100. Dampers are used on the upper vents to prevent reverse airflow at night.

If a masonry wall for thermal storage is exposed to the exterior, insulation needs to be placed on the exposed side. At the perimeter of foundation walls, use 5 cm of rigid waterproof insulation from top to 40 to 60 cm below grade.

8.2.6 CLERESTORIES AND SKYLIGHTS

Clerestories admit direct gain into spaces that are not on the south side of the building. The ceiling of the clerestory and reflecting walls should be a light color. In general skylights, light pipes, and light chimneys are used for daylighting. One problem with skylights is heat gain in the summer as it is more difficult to shade skylights.

8.2.7 SUNROOM (SOLAR ROOM), ATTACHED GREENHOUSE

Sunrooms and attached greenhouses are commercially available and there are many kits and design plans for those who want to do the construction. The solar gain from the sunroom or attached greenhouse can be enough to heat that structure and the home, especially during fall and spring. However the sunroom or attached greenhouse has major problems in controlling the flow of heat to the rest of the home and overheating in the summer. Without sufficient thermal mass, they will even overheat during spring and fall. Another problem with a sunroom or attached greenhouse is that people will want to extend the growing season of plants and so they have auxiliary heating.

8.2.8 PASSIVE COOLING

Make the roof a light color or reflective material. High temperatures in attics are a major problem, so passive ventilators (which can be covered in winter) are very useful. Now there are reflective paints available for the inside of roofs.

In climates with hot-dry summers open the building up at night (operable windows or vents) to ventilate and cool interior thermal mass. Arrange large openings of roughly equal size so that inlets face the prevailing nighttime summer breezes and outlets are located on the side of the building directly opposite the inlets or in the low-pressure areas on the roof and sides of the building. Close the building up when you get up in the morning to keep the heat out during the daytime.

I used passive cooling for my home in Canyon, Texas, where the climate is temperate, semi-arid. In general the summer nights are cool because the elevation is around 1,100 m. The average low and high temperatures, °C, in the summer months are: June 16.4, 30.8; July 18.5, 32.8; and August 17.7, 31.5 and there are an average of 5.2 days/year with temperatures above 37.8°C (100°F). There is quite a bit of thermal mass since I added a passive room to my home (see Example 8.2). By opening the windows at night and closing them the first thing in the morning, the air conditioner was only used two to three times during the summer, which meant my electrical bill was low compared to my neighbors who keep their homes closed and had the air conditioner on all summer. Note that many women do not like this type of operation because of the dust that enters the home, especially in our area, which has lots of wind and is semi-arid.

In climates with hot-humid summers, open the building up to the prevailing summer breezes during the day and evening. Arrange inlets and outlets as outlined above; only make the area of the outlets slightly larger than the inlets.

8.2.9 OTHER

To improve performance of a passive system may require some manual control, for example opening and closing windows on a daily basis, opening and closing vents on a seasonal basis. One way to improve performance is to use movable insulation on the inside of the building and/or shutters on the outside of the building for all glazed openings to reduce heat loss when the sun is not shining. Single glazing gives a net energy gain in temperature climates and insulation would improve that performance. In cold climates, movable insulation should always be used on single glazing. The insulation must make a tight and well-sealed cover of the glazed opening.

A horizontal reflector roughly equal in width and 1 to 2 times the height of a vertical glazed opening can improve performance. As noted, Steve Baer had a moveable (manual) horizontal reflector with insulation to improve performance.

Vertical glazing on the south should always have overhangs for shading of the summer sun. This still allows daylighting and reduces the direct gain. Software programs are available for calculating amount of overhang by location and time of year.

Before designing or constructing a solar system, obtain climate information and do your background collection of renewable energy systems you might want to employ. Finally, find out types of systems installed in your area and talk to the owners or operators about the performance. The examples show a few of the homes and systems in the area of Canyon, Texas.

FIGURE 8.2 Passive solar home; notice overhang for sunroom, clerestories, and bedrooms.

Example 8.1

This example is of a passive solar home (Figure 8.2) located southeast of Canyon, Texas, on Cemetery Road. The passive systems are direct gain through a sunroom and two clerestories, direct gain on bedrooms situated to the southeast and southwest, an entryway into the house shielded from northern breezes, and only one small window on the north. Thermal mass is from 30 cm (1 ft) wide adobe walls, with the blocks made on site. Note that the clerestories have passive shutters on the inside of the house, with skylids from Zomeworks. The heat from the sun drives liquid from one container to another, changing the balance. Previously, the southeast and southwest bedrooms had additional indirect gain with water barrels (direct gain), which were underneath the direct gain into the room. The water barrels were removed due to corrosion, and the glazing was removed and the openings were closed as the rooms received enough heat from the direct gain. Southwest bedroom direct gain is now completely shaded by a tree during summer.

Example 8.2

This example is of a remodel of a home in Canyon, Texas. The garage at my residence was converted into living space (Figure 8.3a), which has passive heating (direct gain) due to double-pane, low-e windows. The original overhang gives shading in the summer. A slate floor absorbs sunlight, and thermal mass for storage is provided by a slate floor, concrete slab (8 in.), and a brick wall (4 ft high, 24 ft long; the brick has magnesium for higher heat capacity) on the north side of the room (Figure 8.3b). There is a wide opening (6 ft) to the rest of the home, and auxiliary heating and cooling is from an existing HVAC (heating, ventilation, air conditioning) unit. On most sunny days in the winter, the room is solar heated and even provides some heat for the rest of the home. During early fall and late spring, the room provides a substantial portion of heat for the home. During the summer, windows are opened at night for cooling and then closed by 0700 to 0800 in the morning, so the air conditioner is only needed a few times during the summer. Because the elevation is 1,100 m and there is low humidity, in general the nights are cool. The original home had windows on the south in the dining room and bedroom, which in the past provided passive solar heating; however, a partial shading screen over the front and a large evergreen tree in the yard have reduced this heating. For better solar performance, both should be removed.

(a)

(b)

FIGURE 8.3 (a) Outside view at solar noon, May 19; notice shade from overhang is at bottom of wall. (b) Sunlight on slate floor during winter, January 16. There is a little extra radiation due to reflection off snow.

8.3 HYBRID SYSTEMS

Hybrid systems combine one or more design concepts of solar or renewable systems to provide heat, cooling, daylighting, or electricity. In general, passive systems, either direct or indirect gain, are the most cost effective. Again, seek local examples and information on the Internet. A self-sufficient house will be a hybrid system consisting of two or more systems; photovoltaic (PV), wind, solar (hot water, heat), and maybe earth berm or even geothermal. Only high-efficiency appliances; smaller number of electronics such as televisions; substitution of manual equipment for small

(c)

FIGURE 8.3 (continued) (c) Inside view, solar noon, May 19; no direct sunlight, but more than ample daylight. Notice brick wall on north for additional thermal mass.

appliances such as electric can openers; and even a smaller number of lightbulbs are used because of the cost of off-grid electricity and cost for storage (batteries). Again, there will be many local examples, so talk with the owners to find out the best and most cost-effective systems.

Detailed information is presented on the renewable energy demonstration building, Alternative Energy Institute (AEI), West Texas A&M University. The renewable energy demonstration building (Figure 8.4) was located at the AEI Wind Test Center, on the north side of the West Texas A&M University campus. In 2010, the building and Wind Test Center equipment and towers were moved to the Nance Ranch as the university needed the previous location. Information on AEI and the Wind Test Center is available at http://www.windenergy.org.

The three main objectives of the renewable energy demonstration project were as follows:

Work space for research projects at the Wind Test Center
Demonstration of renewable energy systems for builders, contractors, and architects
Education for the general public about renewable energy systems

The performance of the building was monitored, and the information was used in research projects. The metal building is divided into a 30 × 50 ft workroom on the east and a 30 × 25 ft tech room on the west. *No auxiliary sources of heating or cooling were installed*; however, the building is connected to the utility grid. The renewable energy systems are as follows:

Passive solar heating, direct gain, in workroom and tech room
Two active flat-plate (vertical), hot air solar collectors (one with glass and the other with fiberglass reinforced plastic (FRP) glazing), with a common rock storage under 80% of the workroom floor

FIGURE 8.4 Renewable energy demonstration project; PV yard light at right.

Passive daylighting for workroom
Passive cooling in summer with manual control of windows
Solar hot water
Stand-alone PV power for a sign and three PV power yard lights
Ceiling fans for circulating air in the workroom
Generation of electricity
  a. A 10-kW wind turbine connected to the grid through an inverter
  b. A 1.9-kW PV array connected to the grid through an inverter

The passive aspects of the building were designed by L. M. Holder III, an architect. The passive solar heating and cooling and daylighting systems were selected and optimized using computer simulations. The anticipated maximum temperature was lowered 5°F, and the minimum temperature was raised 10°F using the simulation. Using the computer model, it was ascertained that R19 insulation in the walls and R30 insulation in the roof would be optimum. Due to budgetary constraints, the insulation in the walls of the workroom was limited to R13 batts.

The active hot air solar collectors were designed by Jimmy Walker, extension agent, Oldham County, who also assisted AEI in their construction. AEI personnel installed the rest of the systems—solar hot water, wind turbine, PV array, stand-alone PV for lighting and sign—along with providing the design and development of data acquisition and storage and real-time display of the performance of the building and electric generation.

8.3.1 BUILDING

The east-west building is oriented 15° from south, so the south-facing windows and hot air collectors capture more early morning gain during the winter. An air infiltration barrier (Tyvek) was placed around the perimeter of the building; however, the construction contractor did not use proper methods for installation. A ventilated ridge and soffit vent along with a painted radiation barrier on the underside of the roof reduces the impact of the sun during the summer and decreases black sky radiation on clear winter nights. On the north side of the building, there is a minimum number windows, which are placed at a higher level, primarily for nighttime flushing of hot air in the summer. All windows are double pane, low emissivity with wood frames. The foundation is insulated down to 2 ft with 2-in. thick Styrofoam board. Because of improper maintenance, the frames of some of the wood windows rotted, and the windows had to be replaced.

8.3.2 PASSIVE HEATING AND COOLING

The tech room has only passive heating with direct gain. The room has a dropped ceiling and 6 in. of insulation with R19 batt, and the walls are covered by 1/4-in. wood paneling. The thermal mass consists of water tubes next to the south windows (Figure 8.5), the concrete slab floor (6 in), and in addition a concrete block wall filled with vermiculite on the north (Figure 8.6). Because of more insulation and the dropped ceiling, this room is around 5°F warmer on cold days in the winter than the workroom.

In the tech room, two windows on the west and the large window on the north were for viewing of wind turbines at the Wind Test Center. The area of these windows was above the window area recommended from the design simulation, which would have reduced west and north window area to a minimum.

The workroom has direct gain windows, daylighting, and operable windows on the south and north for cooling. The thermal mass for the workroom is a thick concrete slab for the floor and the rock storage. The lower section of the direct gain windows and high windows on the north are operated manually for passive cooling during late afternoon and through the night. All windows should be closed early in

FIGURE 8.5 Water tubes for more thermal mass and added food color became stratified. Note water level due to evaporation because of poor cover. Lower sash on windows has manual opening.

FIGURE 8.6 Concrete block wall filled with vermiculite, 6 ft high, on north wall. High windows on north and low windows on south open for nighttime flushing during summer.

the morning. Manual control is a problem when personnel are not in the building at the end of the working day or the next morning. Manual control by students or personnel who do not have an interest in the project is even more of a problem.

The large east-facing windows in the workroom are for daylighting and passive gain during the winter. They were shaded with angled slats for the summer to keep out the early morning sun; however, they still provide daylighting. Ceiling fans provide increased air movement inside the workroom during the summer.

8.3.3 Solar Hot Air System

Two active solar air collectors (234 ft^2 area) are part of the south face of the workroom (Figure 8.7). One collector has tempered glass glazing (west) and the other FRP glazing (east), as can be seen in Figure 8.4. The FRP has become less translucent over the 20 years of exposure to the sun. Circulating fans, activated by a differential temperature controller, connect to plastic pipe in the rock bed, which consists of 1- to 1.5-in. washed river rock 1 ft deep and with an area of 1,250 ft^2. The 6-in. diameter inlet and outlet pipes (polyvinyl chloride, PVC) are 6 ft apart, with 1-in. diameter holes on 12-in. centers on each side. Even though there is one set of pipes for each collector in the rock storage, the rock storage is shared thermal mass. Additional thermal mass consists of an 8-in. concrete slab over the rock bed.

The collector (Figure 8.8) consists, from front to back, of glazing, 2-in. dead air space, selective surface copper absorber, 2-in. air channel, duct board insulation with aluminum foil, and 3/4-in. plywood, which is the interior wall.

8.3.4 Solar Hot Water

A 32-ft^2 flat-plate collector is mounted on the roof (see Figure 8.4). The storage tank has a heat exchanger for the circulating fluid for the solar collector, and there is no auxiliary heater for the hot water tank since the demand for hot water is low. The

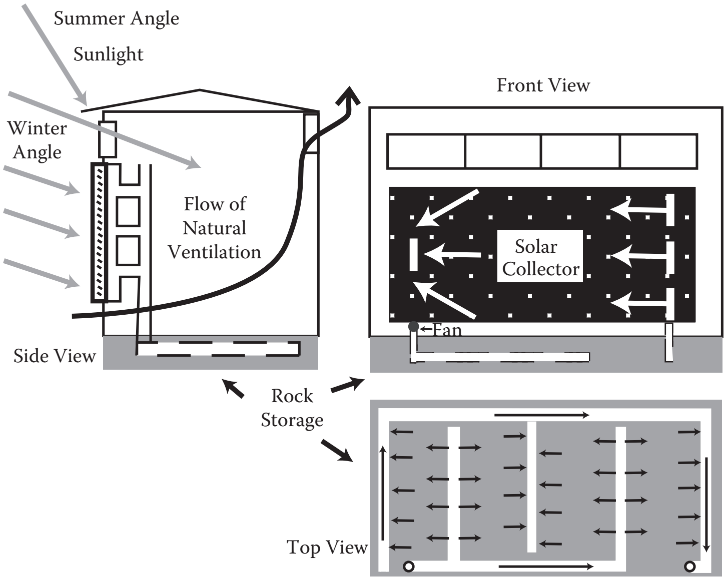


FIGURE 8.7 Left, angle of sunlight for summer and winter plus diagram of airflow at night during summer. Right, diagram of one of the hot air collectors and flow of air during winter collection of solar heat.

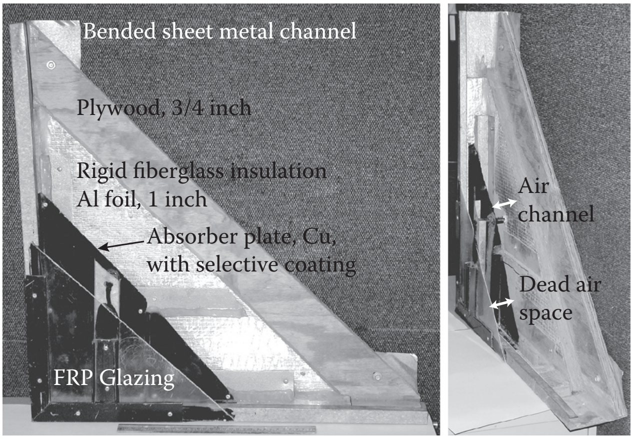


FIGURE 8.8 Cross section of hot air collector.

solar tank and the two inverters are housed in the tech room and are visible through patio doors.

8.3.5 DAYLIGHTING

There is a row of daylighting windows along the top of the workroom. These give direct gain in the winter and are shaded by an overhang in the summer. With the

FIGURE 8.9 Interior of workroom showing that electrical lights are not needed due to daylighting.

direct gain windows, the daylighting windows, the white insulation, and the metal beams painted white, lights are only necessary at night, even on overcast days (Figure 8.9). At 1530 on June 24, the south wall of the building is completely in the shade (no direct sunlight striking the surface) because of the orientation of the building. The east windows in the workroom also provide a significant amount of daylighting. Notice that roof insulation is white, which also assists in daylighting.

8.3.6 ELECTRICAL GENERATION

A wind turbine (10 kW) and a PV array (1.9 kW) are connected in parallel with the load through inverters (Figure 8.10). Two utility meters (ratchet) measure energy purchased from the utility company and energy fed back to the grid. Since installation in 1991 through 2010, the project has been a net electrical energy producer, at a ratio of around 4 to 1. This does not count the displaced energy used on site, which was much larger when an electric van was part of the load at the building (ratio of 3/1).

The wind turbine is a 10-kW permanent magnet alternator with variable voltage and frequency. It is connected to the utility grid though an inverter (12 kW), which changes the output to constant frequency. The wind turbine is mounted on an 80-ft lattice tower next to the building.

A PV 1.9-kW_P array consists of two panels (each panel has sixteen 60-W modules) mounted on the roof with 4 in. clearance underneath for cooling. The two panels are connected in series with a neutral common between them. The positive terminal on one module and the negative terminal on the other module are connected to the inverter, which converts the DC (direct current) power to constant frequency for the grid.

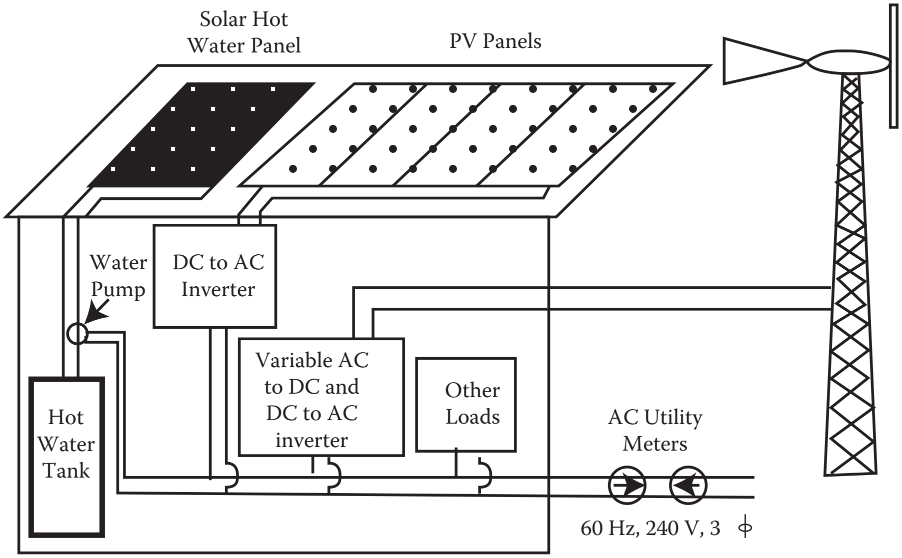


FIGURE 8.10 Diagram of electrical generation.

(a) (b)

FIGURE 8.11 (a) Sign illuminated by fluorescent light powered by (b) PV panel. In right photo, PV-powered yard light is in the background.

There are three stand-alone PV systems for yard lights, which use high-efficiency, low-wattage fluorescent bulbs. One stand-alone PV system provides fluorescent lighting for the demonstration project sign (Figure 8.11), which is lit for 4 h per night. These stand-alone systems have a PV panel, controller, and battery. The yard lights have been a problem, with the battery and lights needing to be replaced within 6 yr.

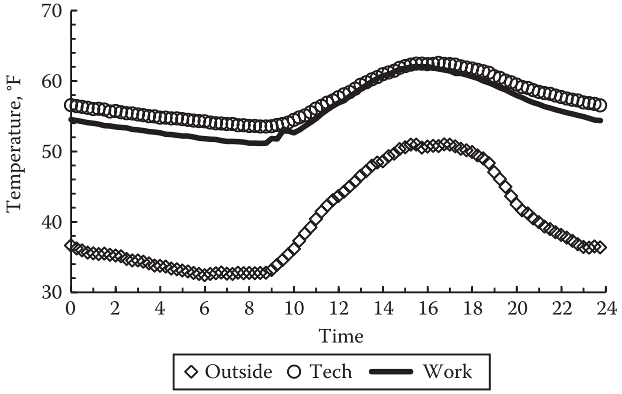


FIGURE 8.12 Average temperature by time of day for February 1988.

8.3.7 PERFORMANCE

There is no auxiliary heating in the winter or air conditioning in the summer for the building. The inside temperatures are within the comfort zone for the functions of the two areas. In the winter, there are days when the outside temperature is 0°F and periods when the temperature is below or near freezing for up to a week. The average outside temperature for December 1998 was 36.3°F. However, in general, when the sun is shining, the outside temperature will rise into the 40s and 50s. The average temperature for July 1998 was 77.8°F, and in the summer, there are days with temperatures over 100°F. Generally, even on hot days when the temperature is over 100°F, it cools off at night because of the 1,100-m elevation.

The temperature for the average day at every 15 minutes was calculated for a winter month and a summer month. For February 1998, the average outside temperature dropped to a minimum of 32°F in the early morning (Figure 8.12). As the sun comes up, the building starts to heat up due to the passive solar, and the temperature reached 60°F in the afternoon. The temperature again drops in the evening hours. There is not much difference between the tech and workroom temperatures, but the workroom temperature is always lower because of the higher ceilings and less insulation in the walls. However, there is more thermal mass in the workroom due to the rock storage.

For August 1998, the temperature of both the workroom and tech room reached 87°F in midafternoon, which is only 3°F cooler than the average outside temperature (Figure 8.13). However, it must be remembered that, on the days when the afternoon temperature is even higher, the inside temperature is still around 87°F. Manual nighttime flushing was not done during this period, as can be seen from the cooler outside temperatures from 2200 at night to 0800 the next morning. If this had been done, then the inside temperatures during the day would have been lower.

Example 8.3

An off-grid home near Amarillo, Texas (Figure 8.14), is discussed here. The home is 150 m^2 (1,600 ft^2); the exterior walls were built from tires (rammed earth fill), with

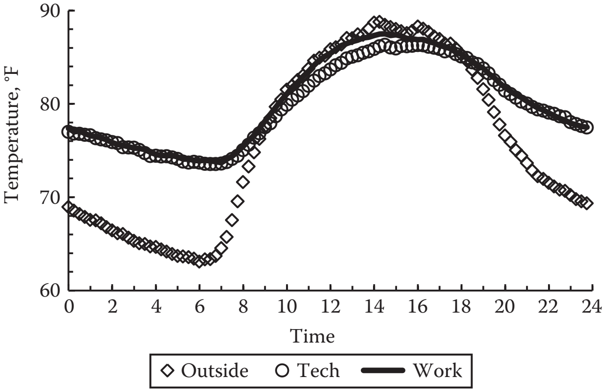


FIGURE 8.13 Average temperature by time of day for August 1988.

FIGURE 8.14 Off-grid home near Amarillo, Texas. South windows for passive, direct gain; PV; wind turbine; and tank for rainwater collection. (Courtesy of David Stebbins.)

passive space heating and cooling (Figure 8.15). The following renewable energy systems were incorporated into the home:

Electric. 0.5-kW PV; 0.9-kW wind turbine; electricity stored in eight deep-cycle golf cart batteries; 4-kW inverter for AC (alternating current) power.

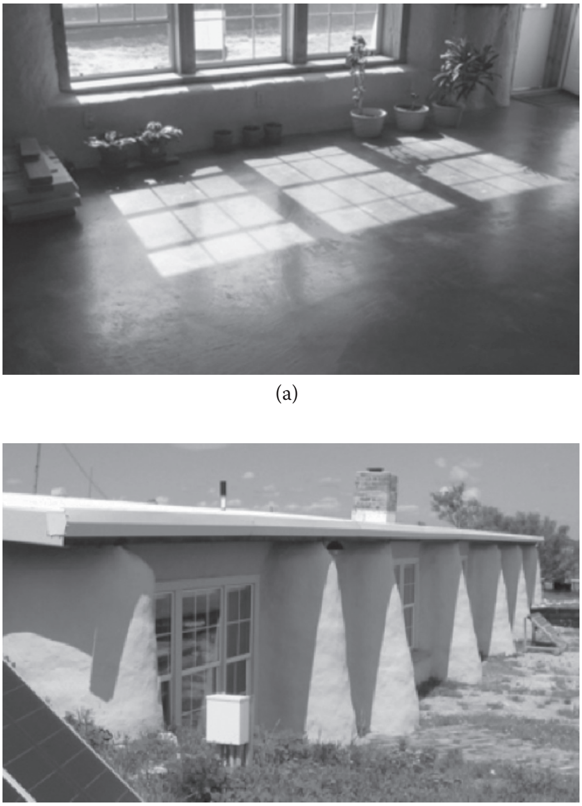
Space heating. Direct gain: thermal mass, concrete slab floor, wood stove backup for cold, cloudy days (around 1 cord/yr).

Space cooling. Overhang shades windows in summer; no air conditioning. Generally, nights are cool, so the house can be opened during the night. Because of the thermal mass, the highest summer temperature was 28°C (83°F).

Solar hot water. Indirect system, solar power pump, 0.2-m^3 (50-gal) tank, 6-gal propane RV (recreational vehicle) heater backup for extended cloudy periods.

Rainwater collection. Metal roof drains to two 6-m^3 (1,600-gal) poly tanks; water pumped through two filtration systems and ultraviolet purifier. Water from carport drains to another 6-m^3 tank for unfiltered water for vegetable garden. Annual average rainfall is 48 cm (19 in.).

Energy use is around 2 kWh/day. As stated, energy conservation is important for off-grid homes, so energy conservation measures include compact fluorescent bulbs, ultraefficient refrigerator, home design that eliminates air conditioning and electric or gas heating, and a front-loading washing machine. Phantom loads are



(a)

(b)

FIGURE 8.15 (a) Winter sun inside; (b) summer sun completely shaded by overhang. (Courtesy of David Stebbins.)

eliminated, such as digital clocks, DVD players, televisions, microwaves, wireless telephones, and so on. The owner has all those items and uses them but plugs them into a power strip that is turned off when the appliance is not in use.

8.4 ACTIVE SYSTEMS

On-demand hot water for residential and commercial users consumes over 3 EJ of energy per year in the United States. Solar hot water systems are the most common active systems, with over 1.5 million installed in homes in the United States, with around 6,000 added annually. Since solar hot water only supplies 2% of total energy now used for heating water, the opportunity for growth is large. System paybacks are 5 to 10 years when displacing electric hot water heaters.

Other countries have higher rates of installation; for example, Israel has around 40% of homes with solar hot water, and laws require all new residences to install solar hot water heaters. Tropical climates are a natural for passive thermosiphon systems.

8.5 UNDERGROUND HOMES

A number of underground homes have been built, so generally you can find one or more homes (Figures 8.16 and 8.17) within a local region. The advantages of underground homes or earth-sheltered homes are as follows:

Conservation of energy
Small range of temperature variation (both heating and cooling)
Low maintenance
Noise insulation
Hazard protection (tornadoes, security) (but a fire exit is needed)
Insurance ought to be less
High-density development possible, efficient use of land, can use land unsuitable for general residential housing
Less dust, longer life

The disadvantages are as follows:

Cost of construction is 10–20% more. Stronger construction is needed for roof to support weight of earth.
Proper water barrier is needed.
  Leaks are hard to find from the inside as actual location of leak can be some distance away.
  Quality installation of butyl sheet or neoprene membranes (bituthene) on outside of concrete is needed.
    Marketability, financing are a problem.
    There is visual isolation; the back rooms only have artificial lights.
    Obtaining a contractor may be difficult.
    The type of soil must be known. Clays will expand and shrink with water absorption to give large forces.

Notice that on the Markham underground home (Figure 8.17) that the large overhang on the south eliminates passive solar for heating. Also, original construction of concrete had too much heat loss on the south, so concrete was covered with 10 cm Styrofoam and then with stucco. One underground home in the area had so many problems with water leaks that they built a roof over the home. Water leaks were due to poor construction techniques, and entrance of leaks on the outside is difficult to find from the inside.

An earth berm can also save energy as it provides a heat sink for part of the structure (Figure 8.18). Heat transfer through the earth for 20 to 30 cm dampens the daily air temperatures, while 2 m of earth essentially gives a constant temperature. Soil temperatures 2 m below ground can be obtained from the local office of the Soil and Water Conservation Service.

There are a number of considerations in designing and building an underground home. On the roof and near exposed areas near the surface, 5 to 10 cm of Styrofoam

(a)

(b)

FIGURE 8.16 (a) Boatwright home, Canyon, Texas; (b) the northern side of home.

insulation is needed. Roof spans need to be less than 7.5 m and can be steel, wood, concrete, or precast concrete. The internal walls need to be load bearing for the extra weight. There is a need to get light into the structure by windows (it is good to have south-facing glazing for solar heating), skylights, or an atrium. An open courtyard in the middle would provide daylighting for all areas of the home.

8.6 COMPUTER SOFTWARE

A number of computer software tools are available. Many tools for whole-building analysis, including renewable energy, are available from the Energy Efficiency and Renewable Energy (EERE) Network, Department of Energy. Architects and builders will also have software for home designs that incorporate solar systems.

RETScreen International provides free software for almost all aspects of renewable energy [2].

(a)

(b)

FIGURE 8.17 (a) Markham home on Cemetery Road, south of Canyon, Texas; (b) northern side of home.

> The RETScreen Clean Energy Project Analysis Software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free of charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs). The software (available in multiple languages) also includes product, project, hydrology and climate databases, a detailed user manual, and a case study based college/university-level training course, including an engineering e-textbook.

The software has been expanded from renewable energy, cogeneration, and district energy to include a full array of clean power, heating and cooling technologies, and energy efficiency measures. Climate data have been expanded to cover the entire surface of the planet, including central-grid, isolated-grid, and off-grid areas, and software has been translated into 35 languages that cover roughly two-thirds of the population of the world.

(a)

(b)

(c)

FIGURE 8.18 (a) Carlson home on Hunsley Hills Road, Canyon, Texas. This is an earth-bermed (west and north side) home built on an abandoned quarry (cheap land). Note that front of house has passive solar, and entrance is a vestibule. (b) Southwest view. (c) Front of house; note same tree; northwest view.

8.7 OTHER

8.7.1 Straw Bale House

In this house, the straw bales, which can be load- or non-load-bearing walls, are plastered on the inside and outside. The advantages are as follows:

Superinsulation, with *R* values as high as R50
Good indoor air quality and noise reduction
Speedy construction process (walls can be erected in a single weekend)
Construction costs as low as \$10 per ft^2 (depending on owner involvement)
Natural and abundant renewable resource used that can be grown sustainably in one season

One problem that has to be avoided is moisture collecting in the straw, which will result in decomposition (rot). Another problem is that bales must be sealed against rodents and even insects.

8.7.2 Adobe and Rammed Earth

Adobe is used throughout the world, even in wet climates, and is popular in the southwestern United States. Adobe, in combination with passive solar design, makes for effective heating in cold winter areas. The use of high-mass walls, insulation, and passive solar can reduce energy use in January by 60% or more. High-mass earth walls also cut cooling costs in hot desert locales.

Rammed earth is a process by which walls of a house are constructed by compacting an earth-cement mixture into forms. The forms are then removed, leaving solid earth walls 45–60 cm thick, which can be load- or non-load bearing (http://www.rammedearthworks.com/).

8.7.3 Tire Houses, Earthships

Tire houses are constructed from used tires filled with earth (Figure 8.19); however, a lot of labor is needed to pack the tires with earth. Outside and inside can then be plastered with a mixture of adobe and cement. Sometimes, bottles and cans are used for space filler for non-load-bearing walls.

8.7.4 Double-Envelope House

Few double-envelope houses have been built because of higher construction costs and problems with performance. The design employs a double envelope with a continuous airspace of at least 15–30 cm on the north wall, south wall, roof, and floor. The south wall is heated by the sun, and during the day, the circulating air warms the inner envelope of the house and gives up heat to the earth or rock storage in the crawl space. At night, the thermal mass releases the heat. The east and west walls are single, conventional walls.

FIGURE 8.19 Zavatsky home, next to Camp Harrington on Ranch Road 1541 near Canyon, Texas. Passive solar home (17 by 6 m) and adjoining workshop (9 by 6 m). Both have tire walls and are bermed on three sides; roofs have R55 insulation and are designed for catching rainwater. (1) Unfinished tire wall in workshop. Notice cans for space filler. (2) Roof of home showing the berm; cistern catchment on left. (3) Interior of the home. (4) Exterior of home; notice overhang for shading during the summer. Photos taken March 27, 2004.

8.7.5 GREEN BUILDING

A significant change is that now green building has become marketable, with builders, associations, and architects promoting green building. Of course, a major aspect of green building is to use solar energy within the local climate. Green buildings are resource efficient in terms of energy and construction materials, including recycled, renewable, and reused resources to the maximum extent practical. Energy efficiency means the use of passive solar and other renewable energy systems when feasible. Green buildings are designed and constructed to ensure that they are healthy for their occupants and are typically more comfortable and easier to live with due to lower operating and maintenance costs. A number of programs are available; again, there is a lot of information on the Internet. The Green Home Building site (http://www.greenhomebuilding.com/index.htm) has information on all aspects of different types of homes: earth, straw, and so on.

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2. RETScreen International. http://www.retscreen.net/ang/home.php.

RECOMMENDED RESOURCES

LINKS

Passive Solar Design

Passive Solar Design, http://www.nmsea.org/Passive_Solar/Passive_Solar_Design.htm

Passive Solar Design Guidelines for Northern New Mexico, http://www.nmsea.org/Education/Homeowners/Detailed_Passive_Solar_Guidelines.php

Sun Plans, http://www.sunplans.com

Passive Solar Design, http://www.apps1.eere.energy.gov/buildings/publications/pdfs/ building_america/29236.pdf

Examples of Solar Homes

Connective loop for transporting heat. http://www.ecohome.com/hernikl/

Maine Solar House. http://www.solarhouse.com/main.htm

North Carolina State University. http://www.ncsc.ncsu.edu/house/solarhouse.html

Solar case studies. http://www.eren.doe.gov/buildings/case_study/casestudy.html

Superinsulation. http://www.public.iastate.edu/~envr_stu_324/house.htm

Components

Natural Home Building Sources, http://www.thenaturalhome.com/passivestuff.html

Sierra Solar Systems, http://www.sierrasolar.com/ssstore/store.htm

Solar Components Corporation, http://www.solar-components.com/solprod.htm

Solar Hot Water

Florida Solar Energy Center. http://www.fsec.ucf.edu/en/consumer/solar_hot_water/index.htm

North Carolina Solar Center, http://www.ncsc.ncsu.edu/

Solar hot water. http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=12850

Underground Homes

A sampling of homes by Davis Caves, http://www.daviscaves.com/homes.htm

Performance Building Systems, http://www.earthshelter.com/home.html

Rob Roy. Earth-sheltered houses. *Mother Earth News*. http://www.motherearthnews.com/Green-Homes/2006–10–01/Earth-sheltered-Homes.aspx

Underground Buildings: Architecture & Environment, http://www.subsurfacebuildings.com/default.asp

Home Sweet Earth Home, http://www.undergroundhomes.com/home.html

Software and Tools

Building Energy Software Tools Directory. http://apps1.eere.energy.gov/buildings/tools_directory/

Design Tools from Sustainable Design. http://www.susdesign.com

DOE sponsored tools. http://apps1.eere.energy.gov/buildings/tools_directory/doe_sponsored.cfm

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OTHER RESOURCES

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Design and construction of a straw bale house, Lowell, VT. http://www.cavedogs.com/building2.html

David Easton. 1996. *The rammed earth house*. Chelsea Green, White River Junction, VT.

Rex A. Ewing and Doug Pratt. 2009. *Got sun? Go solar.* Pixiejack Press, Masonville, CO.

Harvesting, storing and treating rainwater for domestic use. http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/gi/gi-366.html

Home Power Magazine. http://www.homepower.com

William H. Kemp. 2009. *The renewable energy handbook*. Aztext Press, Tamworth, ON, Canada.

S. O. MacDonald and Matts Myhrman. 1998. *Build it with bales: a step by step guide to straw bale construction*. 2nd ed. Treasure Chest Books, Tucson, AZ.

North Carolina Solar House. http://www.ncsc.ncsu.edu/solar_house.php

Ed Paschick and Paula Hendricks. 1995. *The tire house book*. Sunstone Press, Santa Fe, NM.

John Schaeffer. 2007. *Solar living sourcebook*. Galam Real Goods, Louisville, CO.

Straw bale. http://www.strawbale.com

The Last Straw, http://www.strawhomes.com

Athena Swentzell Steen, Bill Steen, and David Bainbridge, with David Eisenberg. 1994. *The straw bale house*. Cheslea Green, White River Junction, VT.

PROBLEMS

There are two 9-ft (2.75-m) by 5-ft (1.5-m) windows for passive solar heating at my home. The wall is 8 ft (2.4 m) tall; the bottoms of the windows are 2 ft (0.6 m) above the ground. The windowpane is 53 in. (1.24 m) tall as the frame takes up some space.

1. Estimate the width of overhang for the window to be completely shaded at solar noon on August 31. Do for a latitude of 35° N, 102° W, in Canyon, Texas. For design information, http://www.susdesign.com, go to overhang design tools.
2. Compare advantages and disadvantages of tire houses and straw bale houses.
3. What should be the orientation and relative shape for a passive solar home?
4. If you were building a solar home, what systems would you use? Why?
5. For an off-grid home, what are the primary considerations for use of electric energy in the home?
6. For an off-grid home, what are the primary considerations for space heating and cooling in the home?
7. How many underground or earth-sheltered homes are in your area? Pick one and describe it.
8. The new term is a *zero-energy home*. What is it? Describe it.
9. Are there any green builders in your area? Get information on one and briefly describe the builder's product or service.
10. What was the coldest outside temperature during the working day for the AEI demonstration building?

11. What was the hottest outside temperature during the working day for the AEI demonstration building?
12. You want to design and build a solar hot water system. Describe the system and components and note the source of the design information.
13. Find an example of a Trombe system, give its location, describe the system size, and estimate the performance or obtain information on actual performance. Do not use examples given in the text.
14. What are the two major problems in constructing an underground home?
15. For new home construction in your country, what renewable systems should be promoted? Give reasons for your answer as if you were head of the national energy department.

9 Wind Energy

9.1 INTRODUCTION

Before the Industrial Revolution, wind was a major source of power for pumping water, grinding grain, and long-distance transportation (sailing ships). Even though the peak use of farm windmills in the United States was in the 1930s and 1940s, when there were over 6 million, these windmills are still being manufactured and used in the United States and around the world [1].

The advantages and disadvantages of wind energy are similar to most other renewable energy resources: It is renewable (nondepleting) and ubiquitous (located in many regions of the world) and does not require water for the generation of electricity. The disadvantages are that it is variable and a low-density source, which then translates into high initial costs. In general, windy areas are distant from load centers, which means that transmission is a problem for large-scale installation of wind farms. The rapid growth of wind power (Table 9.1) has been due to wind farms with 158,500 MW installed by the end of 2009; in addition, there are around 1,000 MW from other applications. There will be overlap between large and small (≤100 kW) wind turbines in the diverse applications of distributed and community wind, wind-diesel, and village power (primarily hybrid systems). Wind turbines for stand-alone and grid-connected systems for households and small businesses, telecommunications, and water pumping are primarily small wind turbines. The numbers installed and capacity are estimates, with better data for wind farms and rougher estimates for the other applications.

TABLE 9.1
Wind Energy Installed in the World, Estimated Numbers and Capacity, End of 2009

Application	No.	Capacity, MW
Wind turbines (primarily in wind farms}	141,000	158,500
Distributed[a]-community	1,300	400
Wind diesel	270	28
Village power	2,000	50
Small wind turbines	650,000	220–270
Telecommunication	500	2–5
Farm windmill	310,000	Equivalent, 155

[a] The overlap between distributed wind turbines and wind farm installations is difficult to distinguish. For example, in Denmark, the large number of distributed units is counted as part of the national capacity.

As of 2009, over 70 countries had installed wind power as most countries are seeking renewable energy sources and have wind power as part of their national planning. Therefore, countries have wind resource maps, and others are in the process of determining their wind power potential, which also includes offshore areas.

During the 1930s, small wind systems (100 W to 1 kW) with batteries were installed in rural areas; however, these units were displaced with power from the electric grid through rural electric cooperatives. After the first oil crisis in 1973, there was a resurgence of interest in systems of this size, with the sale of refurbished units and manufacture of new units. Also as a response to the oil crisis, governments and utilities were interested in the development of large wind turbines as power plants for the grid. Then, starting in 1980s the market was driven by distributed wind in Denmark and the wind farm market in California, which led to the significant wind industry today.

9.2 WIND RESOURCE

The primary difference between wind and solar power is that power in the wind increases as the cube of the wind speed:

$$P/A = 0.5 * \rho * v^3, \text{ W/m}^2 \tag{9.1}$$

where ρ is the air density, and v is the wind speed. The power/area is also referred to as wind power density. The air density depends on the temperature and barometric pressure, so wind power will decrease with elevation, around 10% per 1,000 m. The average wind speed is only an indication of wind power potential, and the use of the average wind speed will underestimate the actual wind power. A wind speed histogram or frequency distribution is needed to estimate the wind power/area. For siting of wind farms, data are needed at heights of 50 m and probably at hub heights. Since wind speeds vary by hour, day, season, and even years, 2 to 3 yr of data are needed to have a decent estimate of the wind power potential at a specific site. Wind speed data for wind resource assessment are generally sampled at 1 Hz and averaged over 10 min (sometimes 1 h). From these wind speed histograms (bin width of 1 m), the wind power/area is determined.

9.2.1 WIND SHEAR

Wind shear is the change in wind speed with height, and the wind speed at higher heights can be estimated from a known wind speed. Different formulas are available [2, Chap. 3.4], but most use a power law.

$$\frac{v}{v_0} = \frac{H}{H_0}^{\,a} \tag{9.2}$$

where v is the estimated wind speed at height H, v_0 is the known wind speed at height H_0, and α is the wind shear exponent. The wind shear exponent is determined from measurements; in the past, a value of 1/7 (0.14) was used for stable atmospheric

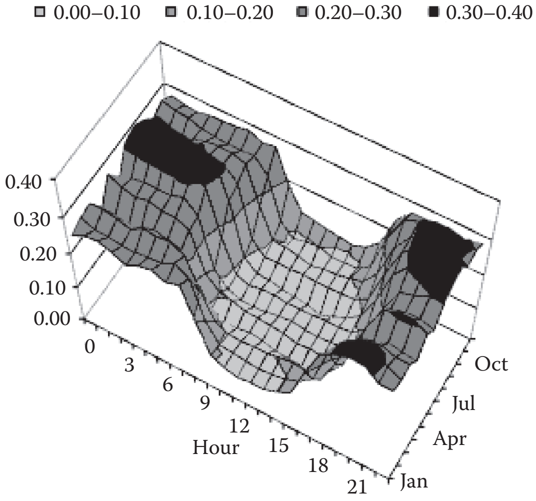


FIGURE 9.1 Annual average wind shear, 10 to 50 m, by month and time of day for Dalhart, Texas.

conditions. Also, this value meant that the power/area doubled from 10 to 50 m, a convenient value since the world meteorological standard for measurement of wind speed was a height of 10 m.

In many continental areas, the wind shear exponent is larger than 0.14, and the wind shear also depends on the time of day (Figure 9.1), with a change in the pattern from day to night at a height around 40 m. This means that wind farms will be producing more power at night when the load of the utility is lower, a problem for the value of the energy sold by the wind farm. There is more power in the wind at 40 m and higher heights than determined by data taken at a height of 10 m (Figure 9.2). The pattern of the data at 50 m for Washburn (not shown on graph) was similar to the 50-m data at White Deer; however, there was some difference between the two sites. Both sites were in the plains, around 40 km apart. This shows that wind power is fairly site specific. Wind data for wind farms has to be taken at heights of at least 40 m to 50 m as at these heights and above the wind pattern will be same, and the wind speeds at higher heights at the same site can be estimated using Equation 9.2. There are some locations, such as mountain passes, where there is little wind shear (Figure 9.3), so taller towers for wind turbines would not be needed.

9.2.2 WIND MAPS

Wind power maps (W/m^2) are available [3] for many countries, regions, and states or provinces within countries. Early maps were for a height of 10 m with an estimate for 50 m using the power law for wind shear (Equation 9.2) and a wind shear exponent of 0.14. The wind power map for the United States (Figure 9.4) shows large areas with wind class 3 and above. More detailed state maps are available. In addition, wind power potential is estimated using geographic information systems (GISs)

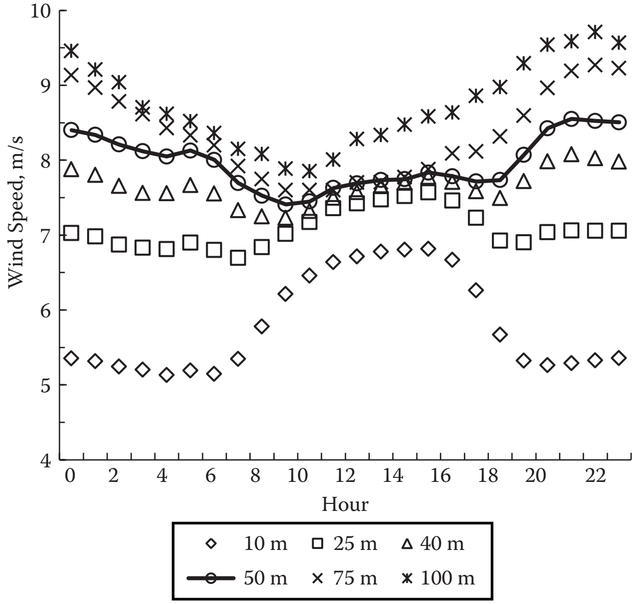


FIGURE 9.2 Average annual wind speed by time of day for White Deer, Texas (10, 25, 40, 50 m), and Washburn, Texas (75, 100 m).

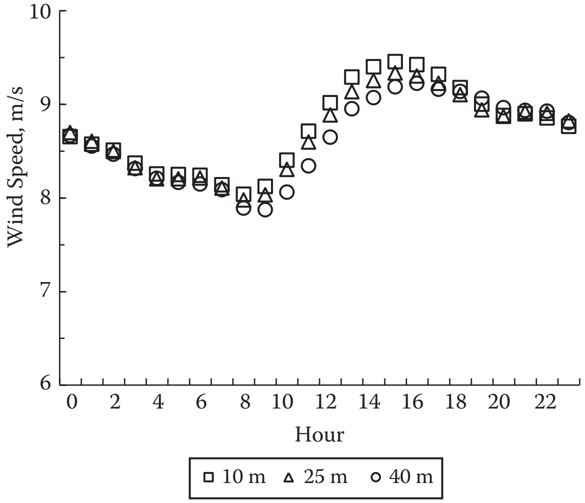
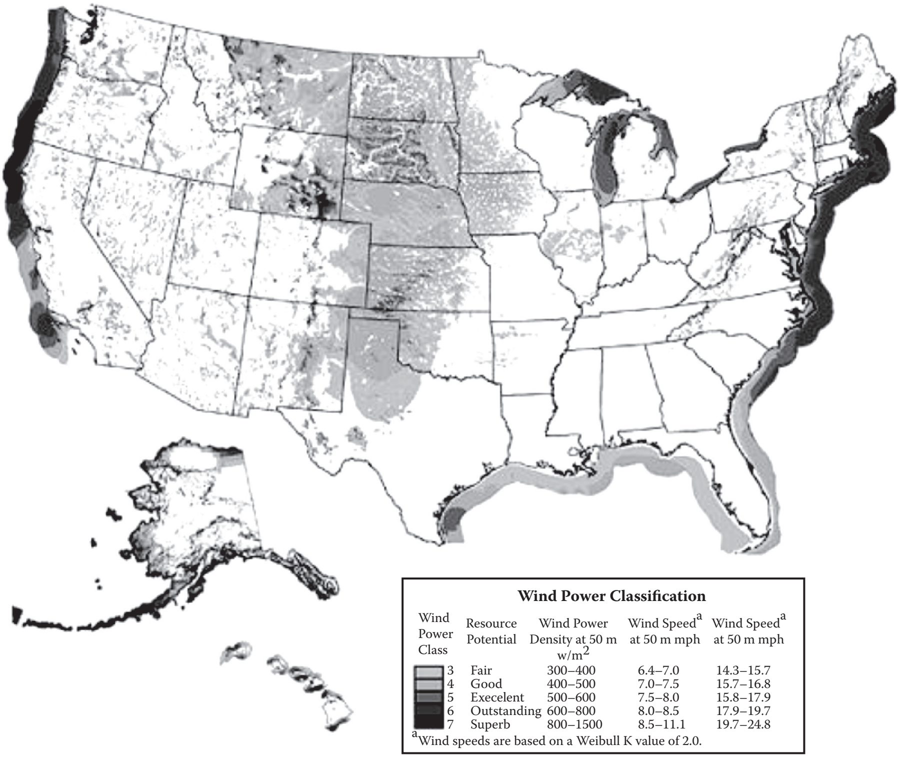


FIGURE 9.3 Average annual wind speed by time of day for Guadalupe Pass, Texas.

with land excluded due to urban areas, highways, lakes and rivers, wildlife refuges, and land a distance from high-voltage transmission lines. The wind power potential is large, so it is not a question of the wind energy resource but a question of locations of good-to-excellent wind resource, national and state policies, economics, and amount of penetration of wind power into the grid. For example, the capturable wind



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m w/m^2	Wind Speed[a] at 50 m mph	Wind Speed[a] at 50 m mph
▨ 3	Fair	300–400	6.4–7.0	14.3–15.7
▨ 4	Good	400–500	7.0–7.5	15.7–16.8
▨ 5	Execelent	500–600	7.5–8.0	15.8–17.9
▨ 6	Outstanding	600–800	8.0–8.5	17.9–19.7
■ 7	Superb	800–1500	8.5–11.1	19.7–24.8

[a] Wind speeds are based on a Weibull K value of 2.0.

FIGURE 9.4 Wind power map at 50 m height for the United States. Notice wind classes. (Map from National Wind Technology Center, NREL, http://www.nrel.gov/wind/resource_assessment.html.)

power potential of Texas is estimated at 223,000 MW, which is much larger than the 110,000 MW generating capacity of the state [4].

Computer tools for modeling the wind resource have been developed by a number of groups: the National Wind Technology Center, National Renewable Energy Laboratory (NREL) in the United States; National Laboratory for Sustainable Energy (RISO) in Denmark; other government laboratories; and private industry. Wind Atlas Analysis and Application Program (WAsP) has been employed in over 100 countries and territories around the world. Now, revised wind power maps for (heights of 50 and 80 m) are available that used terrain, weather balloon data, and computer models [5]; the maps were also verified with available data at heights of 50 m. These maps showed regions of higher-class winds in areas where none was thought to exist. Also, because of the larger wind shear than expected, more areas have suitable winds for wind farm development. Remember that 2–7% accuracy in wind speeds means a 6–21% error in estimating wind power, so data on site are still needed for locations of wind farms in most areas. These maps are a good screening tool for wind farm locations. Interactive wind speed maps by 3Tier [6] and AWS-Truewind [7] are available online for many locations in the world. Wind Atlases of the World contains links for over 50 countries [8].

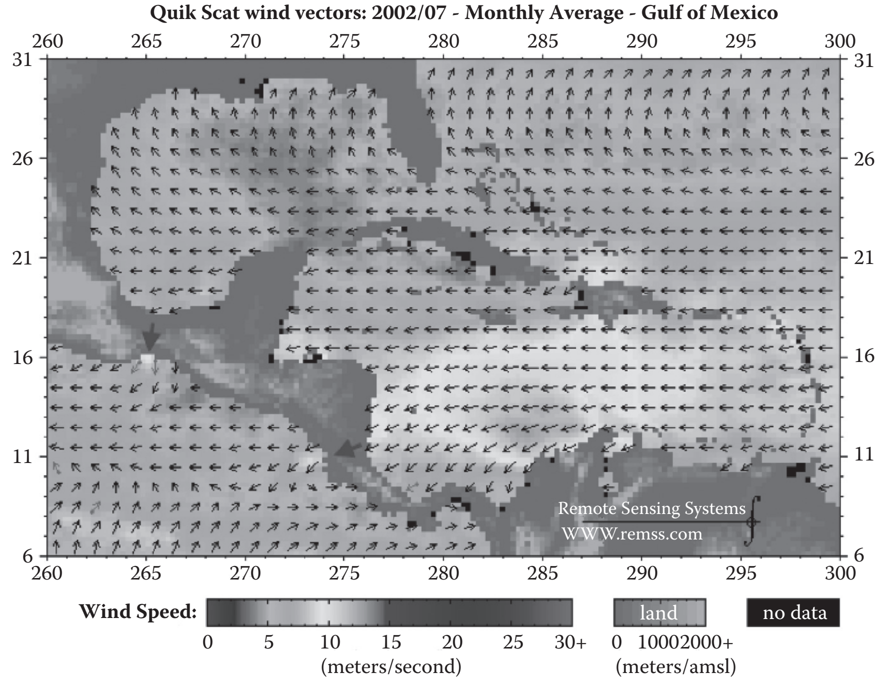


FIGURE 9.5 Ocean winds for July 2002. Two arrows on land indicate excellent onshore wind regions.

Complete coverage of the oceans is now available using reflected microwaves from satellites [9,10]. Ocean wind speed and direction at 10 m are calculated from surface roughness measurements from the daily orbital observations mapped to a 0.25° grid; these are then averaged over 3 days, a week, and a month. Images of the data can be viewed on Web sites for the world, by region or selected area. Ocean winds are not available within 25 km of the shore as the radar reflections of the bottom of the ocean skew the data.

Ocean winds will indicate onshore winds for islands, coasts, and some inland regions of higher winds (Figure 9.5). There are now wind farms in the Isthmus of Teohuantepec, Mexico, and the Arenal region of Costa Rica, where the northeast trade winds (average wind speeds of 10 m/s) are funneled by the land topography.

9.3 WIND TURBINES

Wind turbines are classified according to the interaction of the blades with the wind, orientation of the rotor axis with respect to the ground and to the tower (upwind, downwind), and innovative or unusual types of machines. The interaction of the blades with the wind is by drag, lift, or a combination of the two.

For a drag device, the wind pushes against the blade or sail, forcing the rotor to turn on its axis, and drag devices are inherently limited in efficiency since the speed of the device or blades cannot be greater than the wind speed. The maximum

FIGURE 9.6 Drag device with cup blades, similar to anemometer. (Photo by Charlie Dou.)

theoretical efficiency is 15%. Another major problem is that drag devices have a lot of material in the blades. Although a number of different drag devices (Figure 9.6) have been built, there are essentially no commercial (economically viable) drag devices in production for the generation of electricity.

Most lift devices use airfoils for blades (Figure 9.7), similar to propellers or airplane wings; however, other concepts are Magnus (rotating cylinders) and Savonius wind turbines (Figure 9.8). A Savonius rotor is not strictly a drag device, but it has the same characteristic of large blade area to intercept area. This means more material and problems with the force of the wind on the rotor at high wind speeds, even if the rotor is not turning. An advantage of the Savonius wind turbine is the ease of construction.

Using lift, the blades can move faster than the wind and are more efficient in terms of aerodynamics and use of material, a ratio of around 100 to 1 compared to a drag device. The tip speed ratio is the speed of the tip of the blade divided by the wind speed, and lift devices typically have tip speed ratios around seven. There have even been one-bladed wind turbines, which saves on material; however, most modern wind turbines have two or three blades. The power coefficient is the power out or power produced by the wind turbine divided by the power in the wind. A power curve shows the power produced as a function of wind speed (Figure 9.9). Because there is a large scatter in the measured power versus wind speed, the method of bins (usually 1 m/s bin width suffices) is used.

Wind turbines are further classified by the orientation of the rotor axis with respect to the ground: horizontal axis wind turbine (HAWT) and vertical axis wind

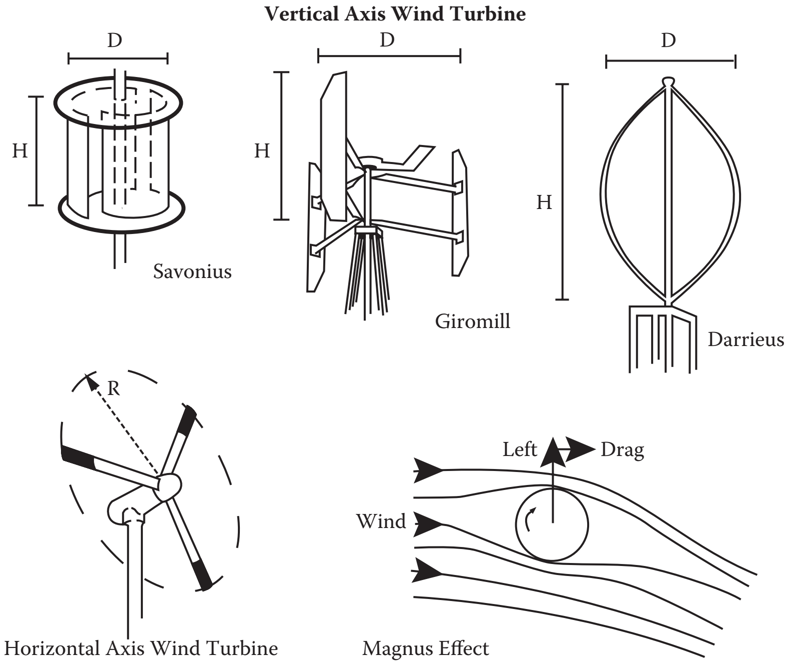


FIGURE 9.7 Diagram of different rotors for horizontal and vertical axis wind turbines.

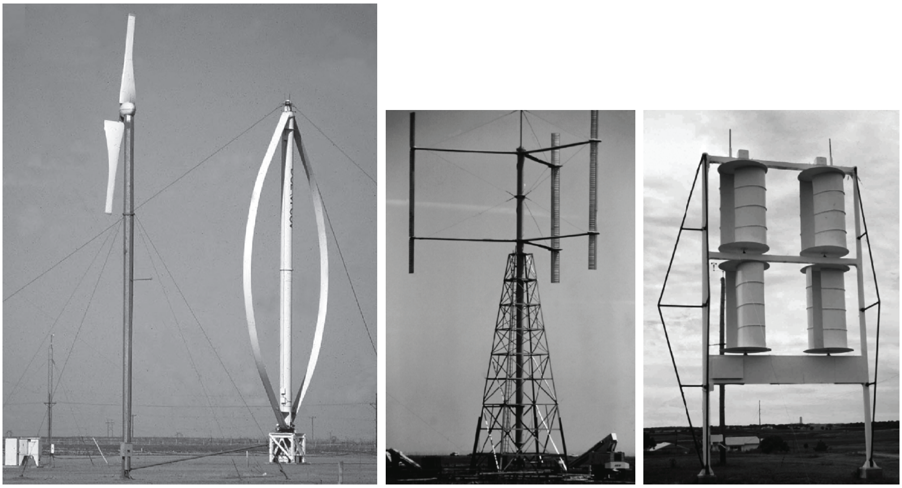

(a) (b) (c)

FIGURE 9.8 Examples of different wind turbines. (a) HAWT, 10 m diameter, 25 kW; Darrieus, 17 m diameter, 24 m tall rotor, 100 kW. (b) giromill, 18 m rotor diameter, 12.8 m high, 40 kW. (c), Savonius, 10 kW. (Courtesy of Gary Johnson.)

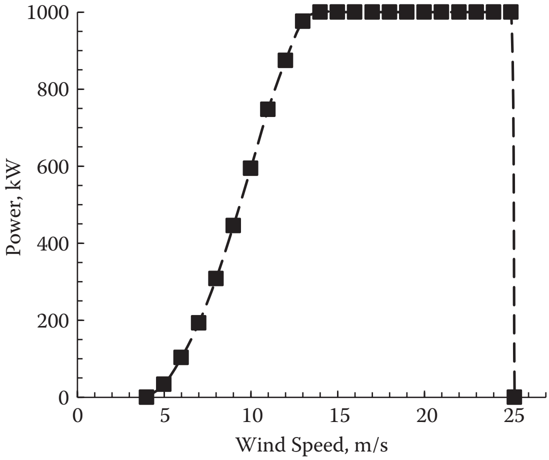


FIGURE 9.9 Power curve for a 1-MW wind turbine.

turbine (VAWT). The rotors on HAWTs need to be kept perpendicular to the wind, and yaw is the rotation of the unit about the tower axis. For upwind units, yaw is by a tail for small wind turbines and a motor on large wind turbines; for downwind units, yaw may be by coning (passive yaw) or a motor.

VAWTs have the advantage of accepting the wind from any direction. Two examples of VAWTs are the Darrieus and giromill. The Darrieus shape is similar to the curve of a moving jump rope; however, the Darrieus is not self-starting as the blades have to be moving faster than the wind to generate power. The giromill can have articulated blades that change angle, so it can be self-starting. Another advantage of VAWTs is that the speed increaser and generator can be at ground level. A disadvantage is that taller towers are a problem for VAWTs, especially for units of wind farm size. Today, there are no commercial, large-scale VAWTs for wind farms, although there are a number of development projects and new companies for small VAWTs. Some companies claim they can scale to megawatt size for wind farms.

The total system consists of the wind turbine and the load, which is also called a wind energy conversion system (WECS). A typical large wind turbine consists of the rotor (blades and hub), speed increaser (gearbox), conversion system, controls, and the tower (Figure 9.10). The most common configuration for large wind turbines is three blades, full-span pitch control (motors in hub), upwind with yaw motor, speed increaser (gearbox), and doubly fed induction generator (allows a wider range of revolutions per minute for better aerodynamic efficiency). The nacelle is the covering or enclosure of the speed increaser and generator.

The output of the wind turbine, rotational kinetic energy, can be converted to mechanical, electrical, or thermal energy. Generally, it is electrical energy. The generators can be synchronous or induction connected directly to the grid or a variable-frequency alternator (permanent magnet alternator) or direct current generator connected indirectly to the grid through an inverter. Enercon has built large wind turbines with huge generators and no speed increaser, which have higher

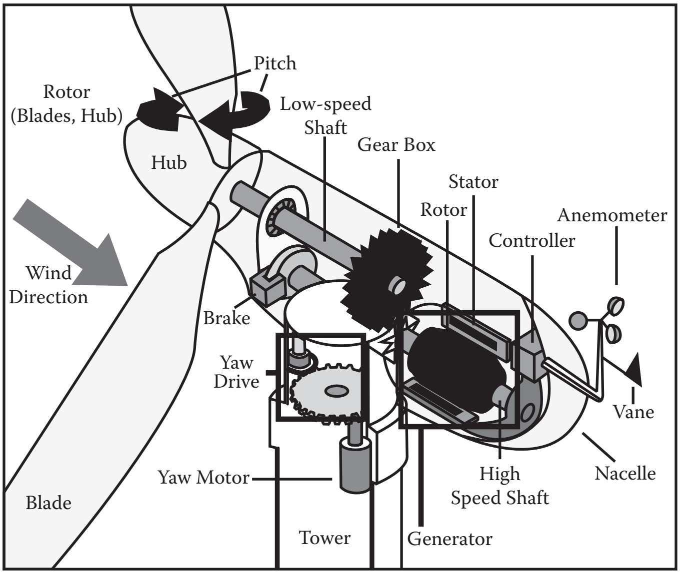


FIGURE 9.10 Diagram of main components of large wind turbine.

aerodynamic efficiency due to variable revolution-per-minute operation of the rotor. However, there are the some energy losses in the conversion of variable frequency to the constant frequency (50 or 60 Hz) needed for the utility grid.

9.4 WIND FARMS

The development of wind farms began in the early 1980s in California with the installation of wind turbines ranging from 20 to 100 kW as those were the only sizes available in the commercial market. This development of wind farms in California was due to U.S. federal laws and incentives (1980–1985) and due to the avoided costs for energy set by the California Public Utility Commission for electricity generated by those wind farms. As the wind farm market in the world continued, there was a steady progression toward larger-size wind turbines due to economies of scale; today, there are commercial multimegawatt units.

Since then, other countries have supported wind energy, and by the end of 2009, there were 158.5 GW installed (Figure 9.11) from around 141,000 wind turbines. These wind turbines generate around $4 * 10^8$ MWh per year. Installation of wind turbines in Europe was led by Denmark in the early days, and its manufacturers captured a major share of the world market in the 1980s. Then, other Europe countries installed large numbers of wind turbines, and Germany became the world leader. In addition, there was consolidation of manufacturers, with both Germany and Spain becoming major players. In 2007–2008, the major wind farm installations shifted back to the United States, with a large number also installed in China (Figure 9.12). China is now ranked at two in the world and expects to continue installing large numbers of wind turbines in wind farms in the coming years due

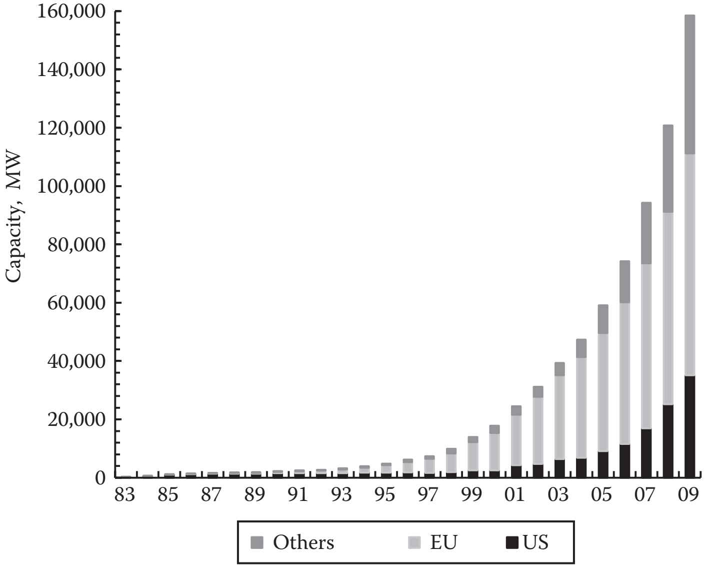


FIGURE 9.11 Wind power installed in the world, 2009, primarily wind farms.

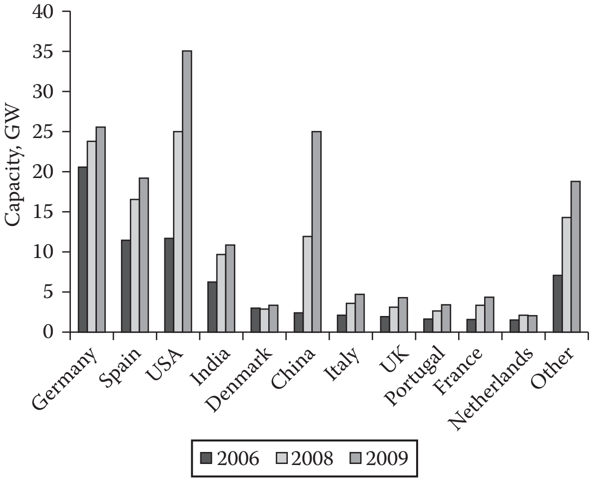


FIGURE 9.12 Cumulative wind power installed by country at the end of the year, primarily wind farms.

to the large increase in demand for electricity; wind farms would also reduce the number of new coal plants due to the requirement of more nonfossil energy in the premier energy consumption for climate change. Although the United States leads in number of wind turbines installed and electricity generated by wind ($7.3 * 10^7$ MWh in 2009), wind energy accounted for only 1.3% of the total electricity generated. However, wind power accounted for 35% of new electric power-generating capacity in the United States in 2009. Other countries obtain a larger share of their electric

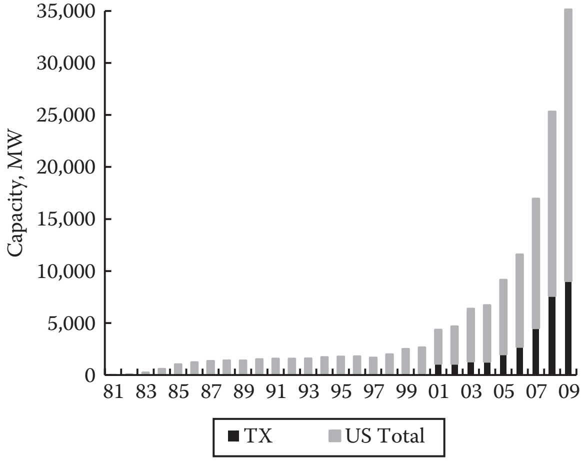


FIGURE 9.13 Wind power installed in the United States, primarily wind farms.

demand from wind, and Denmark is the leader as 21% of its electricity comes from wind power.

Also, there are 2,056 MW (at the end of 2009) installed in 38 offshore wind farms in Europe because of the high cost of land in Europe. Information on European key trends and statistics is available from the European Wind Energy Association and the Global Wind Energy Council. Europe expected another 1,000 MW to be installed offshore in 2010. In China, the first 100 MW offshore wind farm was completed in 2010, and in addition 600 MW offshore and 400 MW intertidal land wind power concession projects were under construction. Thirty GW of offshore wind farms are planned for by the year 2020. Offshore wind farms are being planned for other parts of the world (e.g., in the United States off the East Coast, off the Texas Gulf Coast, and in the Great Lakes).

The growth of installed capacity in the world has been 20–30% per year starting in 2005, but with the present world economic recession, some countries will not experience as large a growth rate in 2010. Texas surpassed California in installed capacity in 2008, and with 9,046 MW (Alternative Energy Institute [AEI] data) installed by the end of 2009, Texas continues to lead the United States (Figure 9.13) in installed capacity [11]. There have been a number of estimates for the future, one being a world wind installed capacity of 240 GW by 2020, which would be a 100% increase over 2008. However, that projection is now low compared to other projections, and it would be equivalent to a growth rate of around 7% per year, which is smaller than growth rates in the past 5 yr for wind power.

Our estimate is that the world wind capacity will be over 600 GW by 2020, an increase of 4,400 MW over 2009. This estimate is due to changes in national policies promoting wind power, primarily in the United States, China, and Europe. Also, the estimate was based on continuing incentives for renewable energy and the construction of high-voltage transmission lines from windy areas to load centers. Wind energy could produce 20% of U.S. electricity by 2030 [12], and if solar, bioenergy, and geothermal energy were included, then renewable energy would provide an even larger percentage of U.S. demand for electricity. The new mandate for China is 150 GW of wind power by 2020, and Europe plans an additional 100 GW by 2020. It is assumed that the rest of the world will install at least 100 GW by the end of 2020. The prospects for the wind industry are excellent, and this does not count the increased numbers of distributed, community, and small wind turbines.

Market forecasts for wind power were seen as overly optimistic at the time of the prediction and then were exceeded every time by the actual amount of installations. World wind capacity grew by over 170% over the 5 yr from 2005 through 2009. Now, the Global Wind Energy Council forecasts 409 GW by the end of 2014 [13], an increase of 251 GW in the next 5 yr.

Wind turbines for wind farms increased from the 100-kW to megawatt size due to economies of scale. There were two different tracks for the development of wind turbines for wind farms. The first was research and development (R&D) plus demonstration projects of large wind turbines for utility power in the 1970s and 1980s, primarily funded by governments. Only prototypes were built and tested [2, see Table 10.10]. The second track was wind turbines in the 50- to 100-kW size built by private manufacturers [14] to meet the distributed market in Europe and for wind farms in California. The manufacturers of the second track were successful in developing the modern wind turbine industry, while the units developed primarily by aerospace companies did not make it to the commercial stage.

There were a number of different designs built and sold in the wind farm market in California, including Darrieus wind turbines. In the United States, the most common designs for two blades were fixed pitch, rotor downwind, teetered hub, induction generator; and for three blades were variable pitch, rotor downwind, induction generator, of which U.S. Windpower built over 4,000 units for the California wind farm market. In Europe, the three-blade, fixed-pitch, upwind rotor model was the predominant design. Now, the three-blades, upwind rotor, full-span, variable-pitch design with a wider range of revolutions per minute is the major type for wind farms. Enercon has a wind turbine with a large generator and no gearbox.

Today, wind turbines are available in megawatt sizes with rotor diameters of 60 to over 100 m installed on 60- to over 100-m towers. Manufacturers are designing and building wind turbines in the 5- to 10-MW size, primarily for offshore installations. Of the top 15 manufacturers in 2007, 10 were from Europe, 2 from China, and 1 each from the United States, Japan, and India. Other major international companies are buying existing manufacturers of wind turbines or starting to manufacture wind turbines for the wind farm market.

Vestas is the leading manufacturer in the world with around 20% of the market, more than 39,000 wind turbines installed, and a capacity greater than 35,000 MW (2009 data). As an example of a large wind turbine installation, a Vestas V90, rated at 3 MW and with a 90-m diameter on an 80-m tower is located north of Gruver, Texas (Figure 9.14). Twenty trucks were needed to haul an 800-metric ton crane to the site, and another ten trucks were needed for the turbine and tower. The weight of the components were as follows: nacelle = 70 metric tons, rotor = 41 metric tons, and tower = 160 metric tons. The foundation required 460 m^3 of concrete and over 40 metric tons of rebar.

FIGURE 9.14 Vestas V90 3-MW wind turbine. Notice minivan next to the tower.

There are economies of scale for installation of wind turbines for wind farms, and in general, most projects need 30 to 50 MW to reach this level. The spacing for wind turbines is three to four rotor diameters within a row and eight to ten rotor diameters from row to row. On ridgelines and mesas, there would be one to two rows with a two-rotor diameter spacing within a row. In general for plains and rolling terrain, the installed capacity could be 5–10 MW/km^2 and for ridgelines 8–12 MW/linear kilometer. Satellite images show the layout of wind farms (Figure 9.15); however, the maps may not show the latest installations. In Texas in 2009, there were five wind farms over 500 MW, and the largest was Roscoe at 782 MW.

9.5 SMALL WIND TURBINES

There are a number of different configurations and variations in design for small wind turbines (watts to 100 kW). Many of the small wind turbines have a tail for both orientation and control in high winds. There are around 650,000 small wind turbines in the world with a capacity around 220–270 MW [2, Chap. 10.2]; however, these are rough estimates. China has produced around 300,000 small wind turbines, primarily from 50 to 200 W (Figure 9.16) stand-alone systems with battery storage. Now, China is starting to build units in the 1- to 50-kW range. In the United States and Europe, approximately 25% of the small wind turbines are connected to the grid.

In 2009, there were around 100 manufacturers of small wind turbines, with around 40 in Europe and 30 in China, and there was a resurgence of VAWTs designs. Marlec, Ampair, and Southwest Windpower produced a large number of micro wind turbines (50 to 400 W). The United States is a leading producer of small wind turbines in the 1- to 50-kW range, and the installed capacity of small wind

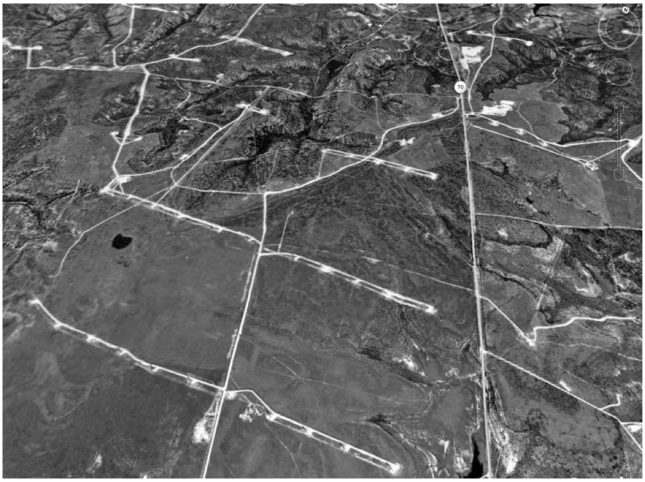


FIGURE 9.15 Satellite view of layout of part of the Sweetwater wind farm (south of Sweetwater, Texas). Notice distance between rows is larger than distance between wind turbines within a row. Rows are perpendicular to predominant wind direction.

FIGURE 9.16 Small wind turbine, 50 W, isolated household, Inner Mongolia, China. Notice rope on tail for manual control; however, this control mechanism is not recommended by manufacturer.

turbines in the United States is around 80 MW. The National Wind Technology Center at NREL has a development program for small wind turbines. Wind energy associations around the world generally have a small wind section, and the American Wind Energy Association has Global Market Studies and a U.S. Roadmap [15]. The Roadmap estimates that small wind turbines could provide 3% of U.S. electrical demand by 2020.

FIGURE 9.17 China village power system (PV/wind/diesel), 54 kW. (Courtesy of Charlie Dou.)

9.6 VILLAGE POWER

Village power is another large market for small wind turbines as approximately 1.6 billion people do not have electricity; extension of the grid is too expensive in rural and remote areas with difficult terrain. There are around 2,000 village power systems with an installed capacity of 55 MW. Village power systems are minigrids, which can range in size from small microgrids (<100 kWh/day, ~15 kW) to larger communities (tens of megawatt hours per day, hundreds of kilowatts). Today, there is an emphasis on systems that use renewable energy (wind, photovoltaic [PV], mini- and microhydro, bioenergy, and hybrid combinations). These systems need to supply a reliable, however limited, amount of energy, and in general much of the cost has to be subsidized. The other components of the system are controllers, batteries, inverters, and possibly diesel or gas generators. In windy areas, wind turbines are the least-cost component of the renewable power supply, and one or multiple wind turbines may be installed in the 10- to 100-kW range.

China leads the world in installation of renewable village systems, of which 100 include wind [2, Chap. 10.5.1]. Their Township Electrification Program in 2002 installed 721 village power systems with a capacity over 15 MW (systems installed: 689 PV, 57 wind/PV, and 6 wind). An example is the village power system (54 kW) for Subashi, Xinjiang Province, China (Figure 9.17), which consisted of 20-kW wind, 4-kW PV, 30-kVA diesel, 1,000-Ah battery bank, and a 38-kVA inverter. The installed cost was $178,000 for power and minigrid, which is reasonable for a remote site.

9.7 WIND DIESEL

For remote communities and rural industry, the standard for electric generation is diesel power. Remote electric power is estimated at 12 GW, with 150,000 diesel gensets ranging in size from 50 to 1,000 kW. In many locations, these systems are subsidized by regional and national governments.

FIGURE 9.18 Wind turbines for diesel fuel saving at Kotzebue, Alaska. In the photo are seven Atlantic Orient wind turbines, 50 kW.

Diesel generators have low installed costs; however, they are expensive to operate and maintain, especially in remote areas. Even with diesel generators, for many small villages electricity is only available for a few hours in the evening. Costs for electricity were in the range from \$0.20 to \$0.50/kWh; however, as the cost of diesel increases, the cost per kilowatt hour increases.

Wind turbines can be installed at existing diesel power plants at a low (fuel saver as the diesel does not shut down), medium, or high penetration (wind power supplies more of the load, which results in better economics as diesel engines may be shut down). The wind turbines may be part of a retrofit, an integrated wind-diesel system, or wind/PV/diesel hybrid systems for village power. Rough estimates indicate that there are over 220 wind-diesel systems in the world, ranging in size from 100 kW to megawatts. Reports on operational experiences from 11 wind-diesel systems are available from a 2004 wind diesel workshop [16].

At Kotzebue, Alaska, there are six diesel generators (11.2 MW, annual average load = 2.5 MW, peak load = 3.9 MW), and the large reserve capacity is to prevent any loss of load during the winter. The cost of electricity was around \$0.50/kWh. Consumption of diesel fuel was around 5.3 million liters per year, with an average conversion of 4 kWh/L. There are 17 wind turbines (Figure 9.18) located on a flat, windy plain 7 km south of town and 0.8 km from the coast. In 2007, the wind turbines generated 667,500 kWh for a savings of 172,000 L of diesel fuel.

In 1996, the U.S. Air Force installed four 225-kW wind turbines connected to two 1,900-kW diesel generators (average load 2.4 MW) on Ascension Island [17] for a low-penetration (14–24%) system. Tower height was limited to 30 m due to available crane capacity on the island. In 2003, two additional wind turbines (900 kW each), along with a boiler and advanced controller, were installed, and that brought the average wind penetration to 43–64%. Fuel savings was approximately \$1 million/year.

A number of wind turbine manufacturers have wind-diesel, hybrid, and even hydrogen production options. These range from simple, no storage systems to complex, integrated systems with battery storage and dump loads.

9.8 OTHER

There is an overlap of small and large wind turbines installed for the wind-diesel and distributed markets. Distributed systems are the installation of wind turbines on the retail or consumer side of the electric meter for farms, ranches, agribusiness,

FIGURE 9.19 Two 1.5-kW wind turbines at telecommunication system, China. (Courtesy of Charlie Dou.)

and small industries and small-scale community wind for schools and other public entities. Examples are as follows:

One 660-kW wind turbine at the American Wind Power Center and Museum, Lubbock, Texas
Ten 1-MW wind turbines at a cottonseed oil plant, Lubbock, Texas
Eight 50-kW units installed in three school districts in towns near Lubbock, Texas
Four 1.5-MW wind turbines that supply electricity for the city of Lamar, Colorado.

There were approximately 300 MW of community wind projects installed in the United States by 2008. The market in the United States for distributed wind is estimated to be at 3,900 MW by 2020 [18]. A *Community Wind Development Handbook* was developed for Minnesota [19]. In Denmark in 2008, individuals or wind turbine cooperatives owned around 80% of the 5,000 wind turbines and had around 77% of the capacity.

Another market for small wind turbines is power for telecommunication stations, with an estimated 500 having small wind turbines as part of the power supply (Figure 9.19). This is a growing market due to the increased use of cellular phones, especially in the more remote areas of the world.

Small PV-wind systems for street lighting (Figure 9.20) are now on the market. Even though there may be a transmission line nearby, the cost of the transformer and electricity is more than the cost of electricity from the PV-wind system.

FIGURE 9.20 PV-wind powers streetlight and flashing red lights at stop signs, McCormick Road on I27 between Canyon and Amarillo, Texas.

Innovative wind turbines have to be evaluated in terms of performance, structural requirements, operation and maintenance, and energy production in relation to constraints and cost of manufacturing. Most innovative wind systems are at the design stage, with some even making it to the prototype or demonstration phase. If they become competitive in the market, they would probably be removed from the innovative category. Some examples are tornado type, tethered to reach the high winds of the jet stream; a tall tower to use rising hot air; torsion flutter; electrofluid; diffuser augmented; and multiple rotors on the same shaft. There have been numerous designs, and some prototypes have been built that have different combinations of blades or blade shapes.

There are also companies that are building wind turbines to mount on buildings in the urban environment [2, Chap. 9.1]. There is an Internet site for urban wind [20] with downloads available. The wind turbine guideline includes images of flow over buildings and example projects. An unusual design for a building is the incorporation of three wind turbines (225 kW each) on the causeways connecting two skyscrapers in Bahrain [21].

The farm windmill is a long-term application of the conversion of wind energy to mechanical power, and it is well designed for pumping small volumes of water at a relatively high lift. It is estimated that there are around 300,000 operating farm windmills in the world, and the annual production of farm windmills is around 3,000. The rotor has high solidity and a large amount of blade material per rotor-swept area, which is similar to drag devices. The tip speed ratio is around 0.8, and the annual average power coefficient is 5–6% [1].

Different research groups and manufacturers have attempted to improve the performance of the farm windmill and to reduce the cost, especially for developing countries [2, Chap. 10.6]. A wind-electric system is more efficient and can pump enough water for villages or small irrigation. The wind-electric system is a direct connection of the permanent magnet alternator (variable voltage, variable frequency) of the wind turbine to a standard three-phase induction motor driving a centrifugal or submersible pump. Annual power coefficients are around 10–12%.

9.9 PERFORMANCE

In the final analysis, performance of wind turbines is reduced to energy production and the value or cost of that energy in comparison to other sources of energy. The annual energy production (AEP) can be estimated by the following methods:

Generator size (rated power)
Rotor area and wind map values
Manufacturer's curve of energy versus annual average wind speed

The generator size method is a rough approximation as wind turbines with the same size rotors (same area) can have different size generators, but it is a fairly good first approximation.

$$AEP = CF * GS * 8{,}760, \text{ kWh/yr or in MWh/yr} \tag{9.3}$$

where AEP is the annual energy production, CF is the capacity factor, GS is the rated power of the wind turbine, and 8,760 is the number of hours in a year.

The CF is the average power divided by the rated power. The average power is generally calculated by knowing the energy production divided by the hours in that time period (usually a year or can be calculated for a month or a quarter). For example, if the AEP is 4,500 MWh for a wind turbine rated at 1.5 MW, then the average power = energy/hours = 4,500/8,760 = 0.5 MW, and the CF would be 0.5 MW/1.5 MW = 0.33 = 33%. So, the CF is like an average efficiency.

CFs depend on the rated power versus rotor area as wind turbine models can have different size generators for the same size rotor or the same size generators for different size rotors for better performance in different wind regimes. For wind farms, CFs range from 30% to 45% for class 3 wind regimes to class 5 wind regimes.

Example 9.1

Estimate the AEP for a 2-MW wind turbine in a class 4 wind regime. Since class 4 is a good wind regime, *CF* = 40% = 0.40. Use Equation 9.3.

$$AEP = 0.4 * 2 \text{ MW} * 8{,}760 \text{ h} = 7{,}000 \text{ MWh/yr}$$

Availability is the time the wind turbine is available to operate, whether the wind is or is not blowing. The availability of wind turbines is now in the range of 95–98%. Availability is also an indication of quality or reliability of the wind turbine. So, the AEP in the example is reduced to 6,650 MWh/yr for an availability of 95%. If the wind turbine is located at higher elevations, then there is also a reduction for change in density (air pressure component) of around 10% for every 1,000 m of elevation.

Since the most important factors are the rotor area and the wind regime, the AEP can be estimated from

$$\text{AEP} = \text{CF} * Ar * W_M * 8.76, \text{ kWh/yr} \tag{9.4}$$

where Ar is the area of the rotor (m^2); W_M is the value of power/area for that location from the wind map (W/m^2); and 8.76 h/yr converts watts to kilowatts.

Example 9.2

For a wind turbine with rotor diameter of 60 m in a region with 450 W/m^2. Assume the CF is 0.40.

$$\text{Rotor area} = \pi * r^2 = 3.14 * 30 * 30 = 2{,}826 \text{ m}^2$$

$$\text{AEP} = 0.40 * 2{,}826 * 450 * 8.76 = 4{,}450 \text{ MWh/yr}$$

If the availability is 95%, then the AEP = 4,200 MWh/yr.

The manufacturer may provide a curve of AEP versus annual average wind speed (Figure 9.21), where AEP is calculated from the power curve for that wind turbine and a wind speed histogram calculated from average wind speed using a Rayleigh distribution [2, Chap. 3.11].

The best estimate of AEP is the calculated value from measured wind speed data and the power curve of a wind turbine (from measured data). The calculated AEP is just the multiplication of the power curve value times the number of hours for each bin (Table 9.2). If the availability is 95% and there is a 10% decrease due to elevation, then the calculated energy production would be around 2,600 MWh/yr.

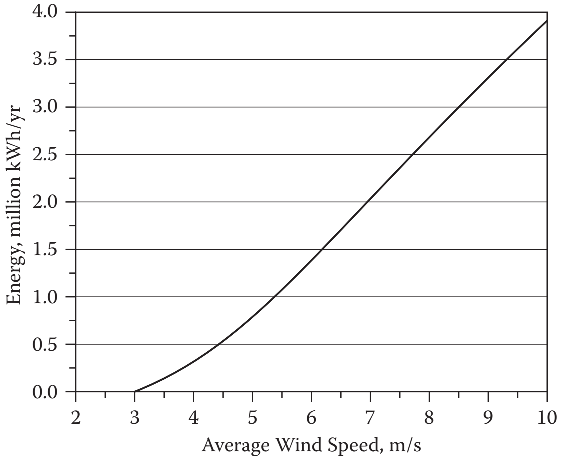


FIGURE 9.21 Manufacturer's curve for estimated annual energy production as function of average wind speed for 1-MW wind turbine.

TABLE 9.2
Calculated Annual Energy Using Power Curve for 1-MW Wind Turbine and Wind Speed Histogram Data for White Deer, Texas

Wind Speed, m/s	Power, kW	Bin, h	Energy, kWh
1	0	119	0
2	0	378	0
3	0	594	0
4	0	760	171
5	34	868	29,538
6	103	914	94,060
7	193	904	174,281
8	308	847	260,760
9	446	756	337,167
10	595	647	384,658
11	748	531	396,855
12	874	419	366,502
13	976	319	311,379
14	1,000	234	233,943
15	1,000	166	165,690
16	1,000	113	113,369
17	1,000	75	74,983
18	1,000	48	47,964
19	1,000	30	29,684
20–24	1,000	20	39,540
>25	0	20	0
	Sum	8,760	**3,060,545**

Bin width = 1 m/s; data adjusted to hub height of 60 m.

The calculated AEP is the number from which the economic feasibility of a wind farm project is estimated and the number that is used to justify financing for the project. Wind speed histograms and power curves have to be corrected to the same height, and power curves have to be adjusted for air density at that site. In general, wind speed histograms need to be annual averages from 2 to 3 yr of data; however, 1 yr of data may suffice if it can be compared to a long-term database.

9.10 COMMENTS

Wind power from wind farms has become a major component for new power installations in many regions of the world. Annual CFs range from 0.30 to 0.45 at good-to-excellent wind locations. One limitation for wind power is that, in general, windy areas are distant from major load centers, and wind farms can be installed faster than construction of new transmission lines for the utility grid. As wind power increases beyond 20% penetration into the grid, stricter requirements similar to conventional power plants, such as wind power output forecasting, power quality, fault (low voltage) ride through, and so forth, will be required at power grid operators.

If storage becomes economical, then renewable energy and especially wind power will supply even more of the world demand for electric energy. In 2011, pumped storage is most economical and should be considered with long distance extra high voltage transmission lines during national electric power system planning to accommodate more wind and solar power penetration into large grids.

There is a growing market for small wind turbines for stand-alone and grid connection and midsize wind turbines for the distributed and community market. The market potential for village power is large; however, there are still problems, primarily institutional and economic costs for these communities.

Past estimates of future installation of wind power have been low, so now the planned installations are at least feasible, for example, the proposal of 20% by 2030 for the United States [12]. China will probably become the leader in manufacturing of large wind turbines and in installed capacity.

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20. Wind energy integration in the urban environment. http://www.urbanwind.org.
21. Bahrain World Trade Center. http://www.bahrainwtc.com/index.htm.

RECOMMENDED RESOURCES

LINKS

Many countries have wind energy associations.
Alternative Energy Institute. http://www.windenergy.org.
American Wind Energy Association. http://www.awea.org.
Danish Wind Industry Association. http://www.windpower.org/en/knowledge.html. This is a great site; check out Guided Tour and Wind with Miller.
European Wind Energy Association. http://www.ewea.org.
Global Wind Energy Council. http://www.gwec.net.
National Wind Technology Center, NREL. http://www.nrel.gov/wind.

PROBLEMS

1. What is the estimated installed capacity of wind farms in the world? Use the latest data available from http://www.gwec.net.
2. Besides being nondepletable, what are the other advantages of wind power?
3. From the wind power map for Massachusetts or the United States, what is the wind class offshore for Nantucket Sound, south of Cape Cod?
4. From the wind power map for the United States, what wind class for the great plains has the greatest area?
5. On the Internet, find a wind map for any country besides the United States. List country and approximate area with good-and-above wind resource.
6. Calculate power/area when density of air = 1.1 kg/m^3 for wind speeds of 5, 10, 15, 20, 30, and 50 m/s.
7. Calculate the wind speed at 100 m if the wind speed at 50 m is 8 m/s and the shear exponent is 0.21.
8. Why are wind turbines on tall towers?
9. For the latest data available, list the top five countries with wind turbines installed and their capacity.
10. What are two differences between drag and lift devices?
11. What would the wind capacity for the United States need to be to meet 20% of electricity needs from wind by 2030?
12. Are there any wind farms in your region? If yes, give location, name, megawatt capacity, and number of wind turbines.
13. When would wind be considered for village power?
14. What is the difference between low and high penetration for wind-diesel systems?
15. Estimate AEP for a 3-MW wind turbine using the generator size method.
16. Use rotor area and a wind map value of 400 W/m^2 to estimate AEP for a 110-m diameter wind turbine.
17. Use the manufacturer's curve (Figure 9.21) for a 1-MW wind turbine and estimate the AEP for an area with an average wind speed of 8.5 m/s.
18. A 120-MW wind farm produces around 347,000 MWh/yr. What is the CF for the wind farm?
19. Using the latest data available, what is the world installed capacity for offshore wind farms?
20. Go to Reference 12: Approximately how many megawatts would have to be installed per year between 2010 and 2030 for the United States to meet the 30% goal?

10 Bioenergy

10.1 INTRODUCTION

The conversion of solar energy by the fundamental process of photosynthesis is the basis for almost all life. Life that is not dependent on photosynthesis has been found in vents in the deep oceans, a significant scientific discovery; however, it is of no significant importance for the production and consumption of bioenergy. Of course, humans are also dependent on biomass for food, fiber, and energy. In terms of the mass of the Earth, the thin layer of biomass is inconsequential, but it is significant in the regulation of the atmosphere and temperature of the Earth. There are three aspects for biomass: overall biomass (which is essentially steady state; growth, storage, decay), food and fiber (Table 10.1), and bioenergy. In general, around 30% of the primary energy of the world is bioenergy, and in some developing countries, it can be 70–90%. Even in developed countries, the contribution from bioenergy can reach 20% due to a large forest industry, and in some of the developed countries, the contribution of bioenergy has been increasing. It is difficult to estimate the percentage of biomass for food, fiber, and bioenergy in the world, as in the developing world food, fiber, and sources of bioenergy are grown and traded locally.

Satellites are used to estimate global biomass production for land (54%) and oceans (46%), which means the land production (excluding areas with permanent ice cover) is around 430 g of carbon/(m^2/yr), and for the oceans, it is around 140 g of carbon/(m^2/yr). These numbers can be compared to average production per area for different sources of biomass: forests (tropical, temperature), cultivated crops, and microalgae.

The carbon cycle of the Earth is important, and the carbon production due to human activity is around $9 * 10^9$ metric tons/yr, with combustion of fossil fuels at $7 * 10^9$ and deforestation at $2 * 10^9$ metric tons/yr. The total carbon sink is around $5 * 10^9$ metric tons/yr due to photosynthesis and soils (30%), the oceans (25%), and sediments and rocks (<1%), which leaves the difference of $4 * 10^9$ metric tons/yr in

TABLE 10.1
Estimate of World Biomass: Amount and Consumption/Production

Biomass	
Forests	$2 * 10^{12}$ tons
Land storage	3,000 EJ/yr or 95 TW
Production	$104 * 10^{12}$ tons carbon/yr
Food consumption	16 EJ/yr
Bioenergy consumption	40–60 EJ/yr

TABLE 10.2
Carbon Content of Fossil Fuels and Bioenergy Feedstocks, Terajoule (TJ)

	Metric Tons/TJ
Coal (average)	25.4
Oil (average)	19.9
Natural gas (methane)	14.4
Coal 1 ton = 746 kg carbon	
Gasoline, 1 U.S. gal = 2.42 kg carbon	
Diesel/kerosene, 1 U.S. gal = 2.77 kg carbon	
	%
Bioenergy feedstocks	
Wood, wood waste	50
Agriculture residue	45

the atmosphere. So, humans are affecting the carbon cycle, and since there is not enough increase in the carbon sinks of biomass and oceans, then there is an increase of carbon dioxide, a greenhouse gas, in the atmosphere. The question is at what level will carbon dioxide in the atmosphere result in serious climate impacts. What was the climate of the Earth in past geological ages during high concentrations of carbon dioxide in the atmosphere? Therefore, geologists should be able to indicate the coming general climate, temperatures, and sea levels.

So, photosynthesis primarily converts carbon dioxide and water to biomass. The carbon content will vary for biomass, coal (note the big difference for lignite and peat), and even natural gas and petroleum (Table 10.2). Because of the smaller carbon content per energy, the combustion of natural gas is better than coal because there is less emission of carbon dioxide. Of course, moisture content will be higher for biomass, so drying or other methods are used to reduce moisture. However, the moisture content of peat is fairly high.

In the past, biomass, primarily from wood, was the major source of energy in the world, and even today bioenergy provides around 30% of energy consumption for the world. Around 2.6 billion people rely on fuel wood, charcoal, and dung for cooking and heating. Fuel wood consumption has increased 250% since 1960, faster than the growth in population in some countries. For example, in some countries in Africa and Asia, wood and charcoal provide 50% to over 90% of the energy (Table 10.3). The collection of fuel wood for direct use and for the increased consumption of charcoal leads to deforestation and degradation of the land and in some areas exacerbates the problems of drought and desertification. Also, collection of fuel wood is primarily the work of women and children. For example, in the Sahel region of Africa, women walk on average 20 km (12 mi) per day to collect wood, and in the towns, families spend a third of their income on wood or charcoal. However, it takes 10 kg of wood to make 1 kg of charcoal. Dung from cows, buffalos, yaks, and even camels is the other major source of energy for heating and cooking in rural areas. In some cases, the fresh manure may be mixed with straw and water, flattened into patties, and dried.

TABLE 10.3
Wood as Percentage of Total Energy Use in Some African and Asian Countries

Africa	%		%
Mali	97	Nigeria	85
Rwanda	96	Cameroon	83
Burkina Faso	95	Sudan	82
Tanzania	95	Madagascar	80
Chad	85	Sierra Leone	76
Ethiopia	94	Angola	75
Central African Republic	93	Ghana	75
Somalia	91	Mozambique	75
Burundi	90	Kenya	70
Niger	86	Cote d'Ivoire	46
Benin	85	Zambia	37
Asia	%		%
Nepal	98	Pakistan	37
Thailand	63	India	35
Sri Lanka	63	Malaysia	10

Open fires in confined spaces present a major health problem, so efficient stoves save lives and energy; however, the problem for many poor people is the cost of the stoves.

When people think of renewable energy, most think of solar (photovoltaic, PV) and wind energy and do not realize that bioenergy is a major component of renewable energy, even in industrialized countries. In the European Union [1], the bioenergy (Figure 10.1) component of renewable energy is 70% (2007 data), and in the United States, it is 53% (Figure 10.2), around 4% of the total energy consumption. In the United States, that 53% due to biomass is from wood, biofuels, and waste, both solid and liquid (Table 10.4). In the United States, the biomass resource is large (Figure 10.3); however, there are limitations in terms of converting present agricultural crops to bioenergy. For example, the Texas Panhandle is a major producer of crops, but because of the large confined animal feeding industry (feedyards), grain is imported for those feedyards and for ethanol plants located in the area. For the United States, biomass maps are available by source: crop, forest, primary mill and secondary mill residues; urban wood waste; and methane from landfills, manure, and wastewater. In some areas of the world, including the United States, fast-growing trees for bioenergy are now a crop. In Sweden, Latvia, and Finland, bioenergy provides around 25% of the total energy consumption.

10.2 CONVERSION

Bioenergy is obtained from organic matter such as wood, crops, animal wastes, municipal solid and liquid wastes, and even algae and bacteria. The raw material

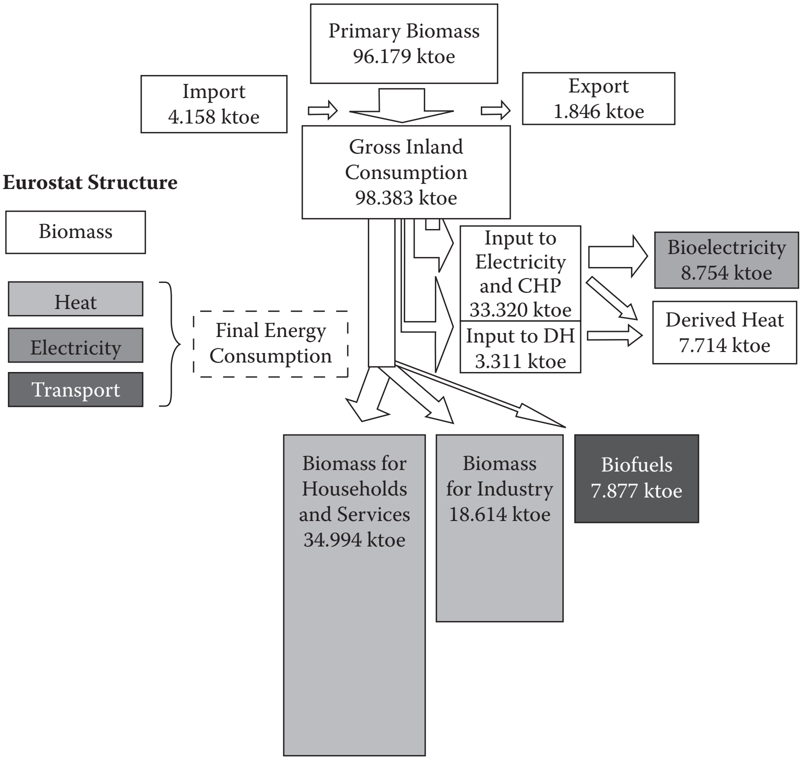


FIGURE 10.1 Bioenergy pathway in the European Union (2007). (Diagram from European Biomass Association.)

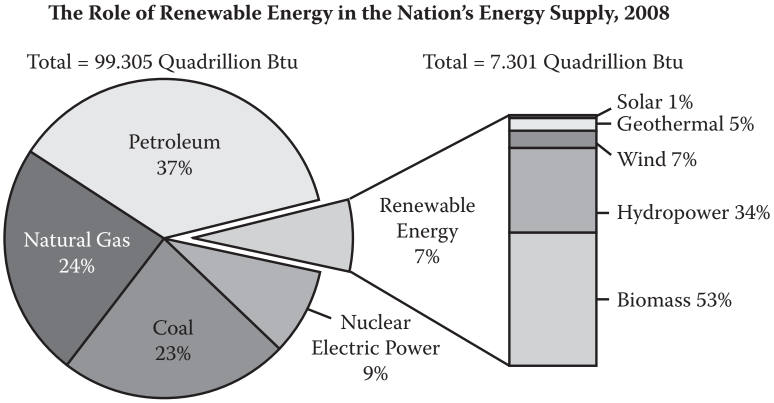
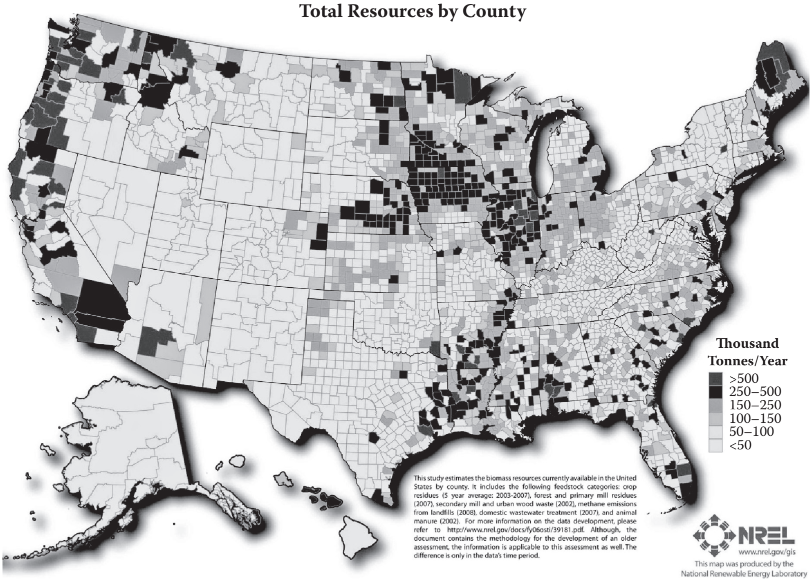


FIGURE 10.2 Energy and renewable energy consumption in the United States. (Diagram from Energy Information Administration, DOE.)

TABLE 10.4
Biomass Energy Production in the United States (2008) for Wood, Biofuels, and Waste (% of Biomass)

	%	%
Wood and derived fuels	52.5	
Biofuels	36.4	
Ethanol		20.8
Losses and coproducts		14.5
Biodiesel		1.1
Waste	11.1	
Landfill gas		4.8
Municipal solid waste		4.3
Other biomass		2.0


Total Resources by County

This study estimates the biomass resources currently available in the United States by county. It includes the following feedstock categories: crop residues (5 year average: 2003-2007), forest and primary mill residues (2007), secondary mill and urban wood waste (2002), methane emissions from landfills (2008), domestic wastewater treatment (2007), and animal manure (2002). For more information on the data development, please refer to http://www.nrel.gov/docs/fy06osti/39181.pdf. Although, the document contains the methodology for the development of an older assessment, the information is applicable to this assessment as well. The difference is only in the data's time period.

This map was produced by the National Renewable Energy Laboratory

FIGURE 10.3 Biomass resource by county for the United States. (Map from NREL, http://www.nrel.gov/biomass.)

(feedstock) is converted into a usable form of energy by combustion or biochemical or thermochemical processes (Figures 10.4 and 10.5). Besides combustion for heat, biomass can be converted to gas and liquid fuels, so a major area of concern is the production of liquid fuels, primarily for transportation.

There are thee major issues with bioenergy. (1) Power plants need to be located near the source of material to keep transportation costs from becoming too large. (2) Energetics has to be considered. What is the energy content of the product

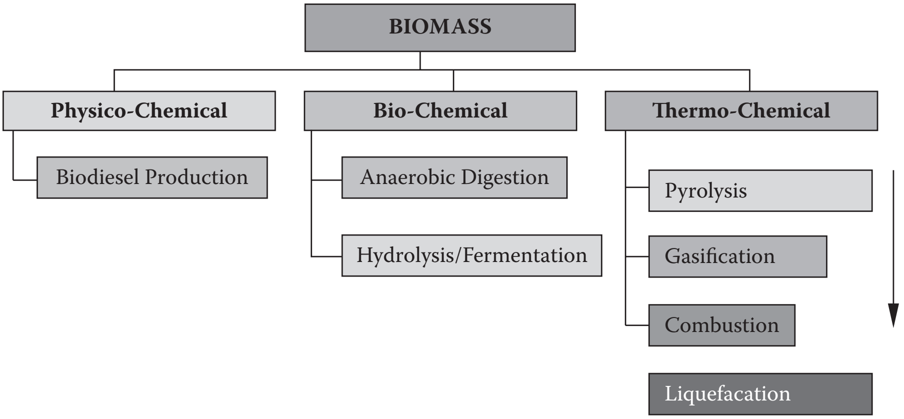


FIGURE 10.4 Diagram of bioenergy conversion. (Diagram from NREL, http://www.nrel.gov/biomass.)

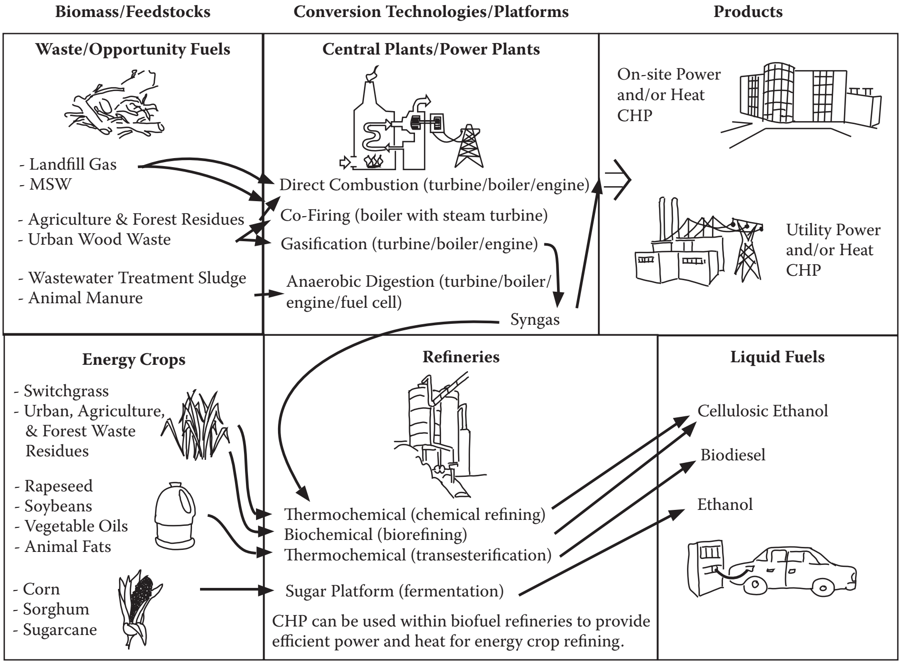


FIGURE 10.5 Conversion of biomass to bioenergy. (From Environmental Protection Agency.)

compared to the energy to make that product? Ethanol produced from irrigated corn is an energy loser, but gasohol has a lot of backing from rural states. In addition, if you take the entire crop residue off the land, what does that do to the soil? (3) In the final analysis, the renewable energy source is the sun, which means that bioenergy has the same attributes of low density and variability in terms of number of crops per year; however, there is less variability for bioenergy than for solar and wind, and there may be a fairly high cost for the conversion plant and transportation. An advantage is the availability of stored energy in the biomass. In other words, how much land area is needed, and will production of bioenergy replace production for food and fiber and increase the cost of food and fiber?

The general end products of bioenergy are heat for households and industry, biofuels (liquid or gas), and electricity. One concept is a biorefinery to produce biofuel, heat or power, and chemicals. A biorefinery could produce one or several low-volume, high-value, chemical products; a lower-value, high-volume liquid fuel; and heat for industrial use or for generation of electricity.

Bioenergy can be obtained from the following:

Crops: corn, sugarcane, potatoes, beets, wheat, sorghum
Oilseed crops: largest source of fats and oils are cottonseed, soybean, rapeseed (canola), palm oil; minor sources are sunflower, peanuts, flax, safflower, sesame, jatropha, Chinese tallow, castor
Agriculture residues: bagasse from sugarcane, corn fiber, rice straw and hulls, nutshells
Major research area: production of ethanol from cellulose
Wood: sawdust, timber slash, mill scrap, paper trash, fast-growing trees like poplars and willows
Municipal solid waste (MSW)
Grasses: fast-growing like switch grass, elephant grass, and prairie bluestem
Methane: landfills, municipal wastewater treatment, manure, lagoons from confined animal feeding
Biodiesel: vegetable oils, animal fats, recycled greases
Petroleum precursors: algae

There may be two harvests per year for annual crops; however, there is still the problem of year-round production for bioenergy. In general, perennial oilseed crops (Table 10.5) have not yet been well adapted to mechanical harvesting. However, once established, they have much higher oil production potential per year than annual crops. Geneticists are trying to convert the major annual crops to perennial crops, which would reduce production costs. Also, if bioenergy crops can be grown on land that is unsuitable for food crops, that is an advantage. A possible problem is that in the tropics more forests are being cleared for plantations of oil palms.

The production of electricity can be by direct combustion or combustible gas. Liquid fuels similar to diesel and petroleum can be obtained in a number of ways: ethanol, biodiesel, vegetable and nut oils, and by algae. Bacteria produce methane from liquid waste and landfills, and researchers are working on bacteria that produce hydrogen.

10.3 HEAT AND POWER

The industrial sector currently produces both steam or hot water and electricity from biomass in combined heat and power (CHP) facilities in the paper, chemical, wood products, and food-processing industries. CHP can improve energy efficiency by 35% over conventional power plants. The forest products industry, which consumes 85% of all wood waste used for energy in the United States, typically generates more

TABLE 10.5
Oilseed Crops, Type, and Percentage Oil

Crop	Potential World	Season	Planting	Oil, %
Cotton	Major	Warm	Annual	17
Soybean	Major	Warm	Annual	18
Peanut	Minor	Warm	Annual	45
Canola	Major	Cool	Annual	40
Flax	Minor	Cool	Annual	35
Sunflower	Major	Warm	Annual	42
Safflower	Minor	Warm (and cool)	Annual	42
Sesame	Minor	Warm	Annual	50
Tung	Potential	Warm/subtropical	Perennial	35
Palm	Major	Warm/tropical	Perennial	35
Camelina	Potential	Cool	Annual	40
Brown mustard	Potential	Cool	Annual	40
Castor	Potential	Warm	Annual	50
Chinese tallow	Potential	Warm	Perennial	31
Jatropha	Potential	Warm/subtropical	Perennial	35

Source: Dr. David Baltensperger, Texas A&M University, Soil and Crop Sciences.

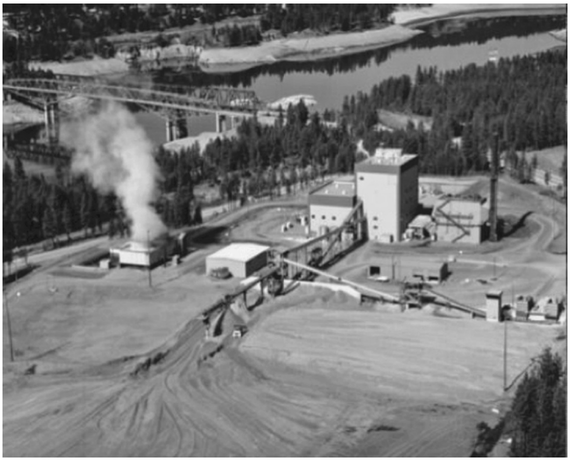


FIGURE 10.6 Power plant fueled by wood, Kettle Falls, Washington. (From NREL, http://www.nrel.gov/biomass.)

than half of its energy from wood waste products and other renewable sources of fuel (wood chips, black liquor). There are 7,730 MW of wood and wood-derived products and 4,454 MW from other biomass; they produced 66 billion kWh of electricity in 2008 in the United States.

Electric power plants can burn the wood or wood waste products directly (Figure 10.6), the biomass can be mixed with coal in small percentages in existing boilers, or the biomass is converted to gas, which is then burned. Commercial, cost-effective technologies for converting biomass feedstocks to electricity and heat currently available [2] are three types of direct-fired boiler systems (fixed bed, fluidized bed, and cofired) for converting woody biomass and then anaerobic digesters for animal waste or wastewater. In the United States, around 500 plants in the range of 10 to 50 MW use biomass as a fuel. Even though these are steam plants, their efficiency is generally in the 20% range, unless they are CHP plants. The biomass is usually low-cost feedstocks, like wood or agricultural waste, which also helps reduce the emissions typically associated with coal. The potential of using biomass for the production of electricity is large; for example, in Texas the burning of 1 million tons/yr of cotton gin trash could produce $1.7 * 10^9$ kWh/yr.

Gasification captures about 65–70% of the energy in solid fuel by converting it into combustible gases. Fixed-bed gasifiers and fluidized bed gasifiers are becoming commercialized and are currently in limited use producing syngas for power and heat. This gas is then burned for process heat or electricity or converted to synthetic fuels. The advantage of biogas over direct combustion is that the biogas can be cleaned and filtered to remove problem chemicals. As an example, during World War II, some vehicles in Europe ran on gas from coal or charcoal.

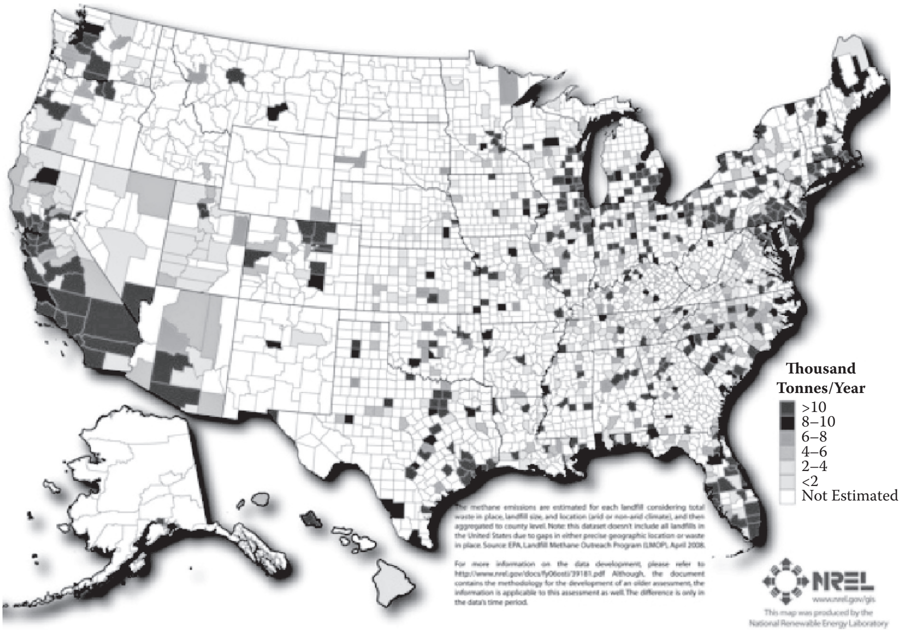
10.3.1 MUNICIPAL SOLID WASTE

The MSW industry has the following components: disposal (landfill) and then possible recycling, composting, or combustion to produce energy. MSW includes durable goods, nondurable goods, containers and packaging, food wastes, yard wastes, and miscellaneous inorganic wastes but does not include industrial waste, agricultural waste, and sewage sludge. Examples of MSW are appliances, newspapers, clothing, food scraps, boxes, disposable tableware, office and classroom paper, wood pallets, rubber tires, and cafeteria wastes.

The disposal of MSW in the United States is a huge problem [3] as 250 million tons of trash were generated in 2008, of which 54% was placed in landfills. Of this, 33% was recovered through recycled material (61 million tons) and compost (22 million tons), and 13% was burned (bioenergy). Recycling and composting have increased from 10% in 1985 to 33% in 2008. Other countries now have regulations that industrial products have to be built with recycling of the material at the end. In the United States, we have to reduce MSW as disposal space is becoming a problem. Where does New York City dispose of its garbage? What happens to old appliances and personal computers in the United States?

10.3.2 LANDFILL GAS

Landfill gas from the decomposition of MSW is about 50% methane, 50% carbon dioxide, and less than 1% other organic compounds. Around 12,200 m^3/day of landfill gas is generated for every 1 million tons of MSW. Landfill gas is a major problem since methane is 20 times worse by weight than carbon dioxide as a greenhouse gas. Methane is at its highest level in the past 400,000 yr and is 150% greater than in 1750. In the past, the landfill gas just seeped into the atmosphere, and for smaller



The methane emissions are estimated for each landfill considering total waste in place, landfill size, and location (arid or non-arid climate), and then aggregated to county level. Note: this dataset doesn't include all landfills in the United States due to gaps in either precise geographic location or waste in place. Source: EPA, Landfill Methane Outreach Program (LMOP), April 2008.

For more information on the data development, please refer to http://www.nrel.gov/docs/fy06osti/39181.pdf. Although, the document contains the methodology for the development of an older assessment, the information is applicable to this assessment as well. The difference is only in the data's time period.

www.nrel.gov/gis

This map was produced by the National Renewable Energy Laboratory

FIGURE 10.7 Resource of landfill gas by county in the United States. (Map from NREL, http://www.nrel.gov/biomass.)

landfills, it is still vented today. In the United States, landfills are the second-largest source of methane (23%) generated by humans. After a landfill is capped, production of landfill gas declines at 2% to 15%/yr.

There is a large potential for landfill gas in the United States (Figure 10.7), and as of 2009, there were 485 operational projects, which generated $2.4 * 10^9$ m^3 of landfill gas per year for direct use and production of electricity, $12 * 10^{12}$ kWh/yr [4–6]. The production of electricity from landfill gas mostly uses internal combustion engines (70%) with rated output of 100 kW to 3 MW. Others use gas turbines (800 kW to 10.5 MW) and microturbines (30 to 250 kW). There is a 50-MW plant at Puente Hills, California, and a 50-MW plant at Inchon, South Korea. Of course, landfill gas can be used for any application that uses natural gas, such as injection into pipelines, burning in boilers, direct combustion, and vehicle fuel. The world largest landfill at Altamont Pass in California is now converting landfill gas to produce 49,000 L/day of liquid natural gas for vehicle use.

In Latin America, there are 117 cities with a population of over 0.5 million that generate 75 million tons/yr of MSW; however, currently only 1 city uses landfill gas to generate electricity, and there are planned projects for only 2 other cities [7]. Case studies from other landfill projects around the world are available.

10.3.3 BIOGAS

Anaerobic bacteria produce methane from liquid waste (municipal, industry, manure), which can be used for heat or electricity. Wastewater treatment facilities

(WWTFs) that have anaerobic digesters generally use the biogas for operations and heat; however, a more efficient use would be CHP.

In the United States, there are more than 16,000 municipal WWTFs, ranging in capacity from 10^6 m^3/day to less than 10^4 m^3/day. Roughly 1,000 of these facilities operate with a total influent flow rate greater than 2 * 10^4 m^3 per day; however, only 544 of these facilities employ anaerobic digestion to process the wastewater, and only 106 WWTFs utilize the biogas produced by their anaerobic digesters to generate heat or electricity. If all 554 WWTFs that have effluent rates of 2 * 10^4 m^3 per day were to install CHP plants, that would add 340 MW of electricity and would reduce CO_2 emissions by 3.2 million tons/yr [8]. For 1.7 * 10^4 m^3/day, enough biogas is generated to fuel around a 100-kW power plant. A list of WWTFs with aerobic digesters and case studies are also given in Reference 8. General rules for considering CHP at wastewater facilities are as follows:

The facility processes 0.4 * 10^4 m^3/day per person.
Approximately 0.3 m^3 of digester gas can be produced per person per day.
The heating value is around 600 Btu/ft^3. Notice that this is a lower heat content than natural gas.

Farmer cooperatives in Denmark and the Netherlands have central biogas CHP plants that use manure. They supply around 40 MW of heat in Denmark and 10 MW of heat in the Netherlands. A plant in Britain uses 146,000 tons of slurry from 28 farms and waste from food processers to provide heat for 1.43 MW of electricity.

Example 10.1

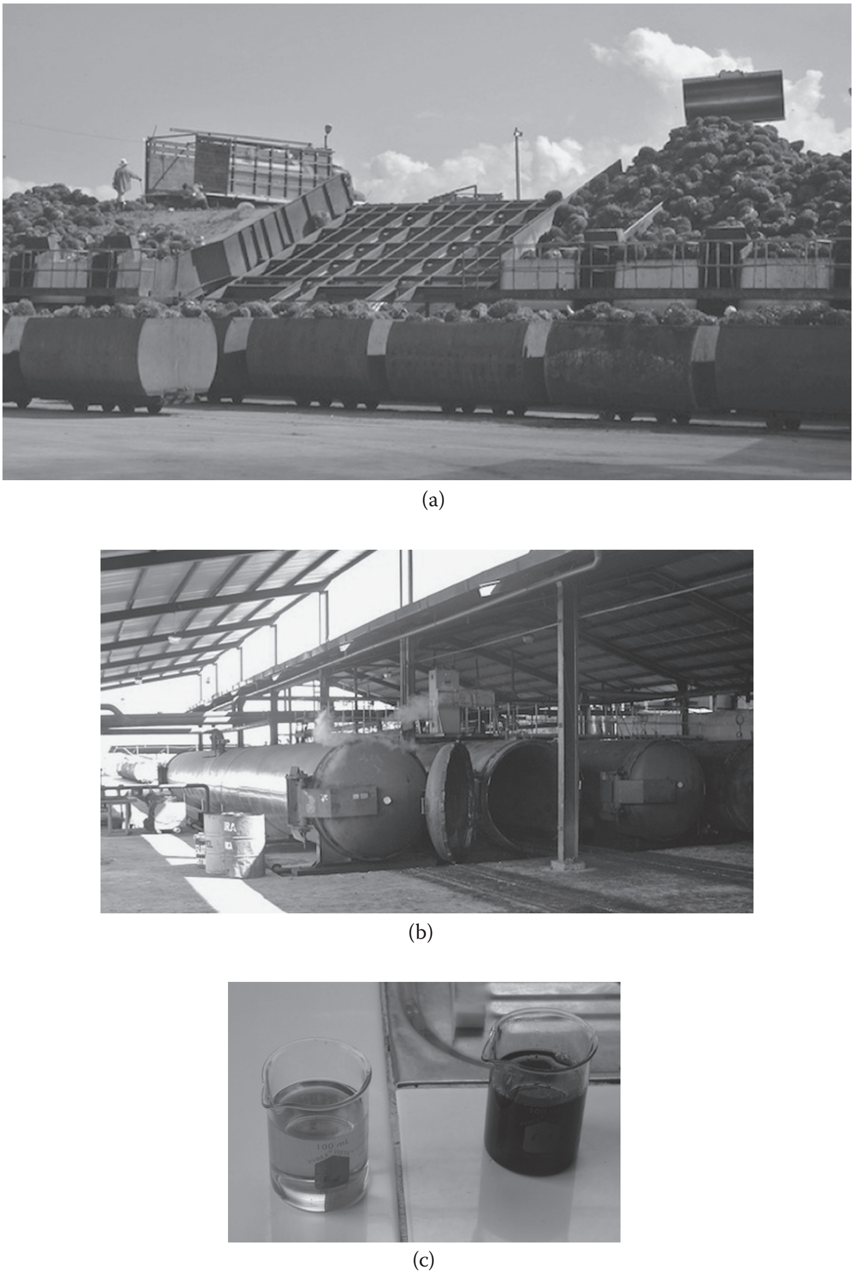
A palm oil facility (Figure 10.8) near San Pedro Sula, Honduras, was formed by 450 farmers. The facility produced 68,000 m^3 of effluent per year, which was discharged to open lagoons; that resulted in 3 * 10^6 m^3 of biogas emission per year. The anaerobic lagoons have been covered with plastic membranes (Figure 10.9), and the biogas now powers two 500-kW diesel generators, which produce around 5.5 GWh/yr that is fed back into the utility grid. The carbon credits are sold to increase the economics of the electric generation.

For any bioenergy system, it takes energy to plant, harvest, and process the material to get the final product, so energy recovery should include all possible paths. In this case, it includes electricity from biogas and solid residue for burning and fertilizer.

10.4 BIOFUELS

World production of biofuels has increased dramatically, and in 2008, the production was 1.5 million barrels/day. For years, Brazil led the world in production of biofuels from the production of ethanol from sugarcane (Figure 10.10); however, increased ethanol production since 2006 has made the United States number one in biofuels.

Projections indicate that up to 30% of the annual liquid fuel demand in the United States could be supplied by approximately 1.3 billion tons from forestry and agriculture



(a)

(b)

(c)

FIGURE 10.8 Palm oil plant near San Pedro Sula, Honduras. (a) Palm nuts from trucks are placed in hopper cars; (b) first step, steam heating of palm nuts in hopper cars; (c) final oil products.

FIGURE 10.9 Palm oil plant near San Pedro Sula, Honduras. Biogas lagoons have plastic covering (top left).

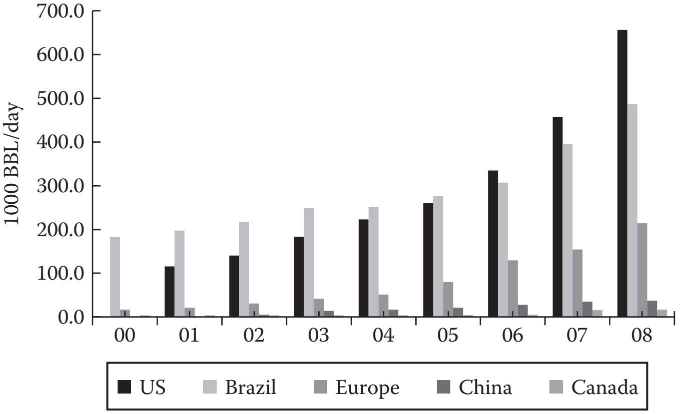


FIGURE 10.10 Leading countries for world production of biofuels.

biomass. The U.S. Department of Energy anticipates that about 800 million tons per year would be supplied from present crop residues and a new generation of dedicated bioenergy crops that are sustainable and integrated with existing food, feed, and fiber cropping systems. Also, almost 400 million tons of forest resources will be needed. For crop residues, a minimum of 1 ton/acre needs to be left behind for soil conservation, 20% is lost in collection, and a crop residue of less than 1 ton/ha is not economical. Countries and even states are mandating through policies and economic incentives a significant increase in the use of biofuels. For example, the renewable fuel standard in the United States will require 36 * 10^9 gal/yr from biofuels by 2022.

Biofuels generally require the following resources or feedstocks:

Sources of sugar and starches (nonstructural carbohydrates)
Lingocellulosic feedstocks
Sources of oils

The first two feedstocks are the biochemical conversion of biomass to biofuels, which involves three basic steps:

Converting biomass to sugar or other fermentation feedstock
  Pretreatment
  Conditioning and enzymatic hydrolysis
  Enzyme development
Fermentation
Processing for fuel-grade ethanol and other fuels

10.4.1 ETHANOL

The production of ethanol accounts for around 90% of the production of biofuels in the world, and production has increased significantly since 2000 due to increased ethanol production in other countries besides Brazil (Figure 10.11). World ethanol production increased from 13.1 * 10^9 gal in 2007 to 17.3 * 10^9 gal in 2008. Ethanol is produced by converting the starch content of biomass feedstocks into alcohol (Figure 10.12). The fermentation process of yeast and heat break down complex sugars into more simple sugars, creating ethanol. The liquid from the fermentation is about 10% ethanol, which then needs to be distilled. The energy content of ethanol is 0.024 GJ/L.

Ethanol is primarily produced from corn (maize in other parts of the world) and sugarcane (Table 10.6). Ethanol can be produced from the cellulose portion of biomass feedstocks like trees, grasses, and agricultural wastes. This process is relatively new; however, there is the potential for using a much wider variety of abundant, less-expensive, and nonfood feedstocks. It is estimated that the United States could produce around half its demand for oil using cellulosic feedstock without affecting food supplies [9].

Ethanol provides a major part of the liquid fuel requirement in Brazil, and production has increased significantly in the United States (Figure 10.13). In the United

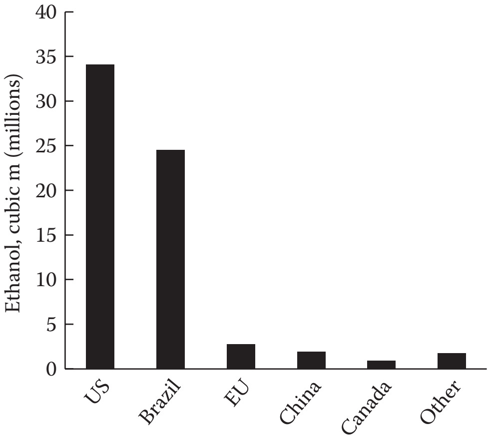


FIGURE 10.11 Ethanol production by major producing countries, 2008.

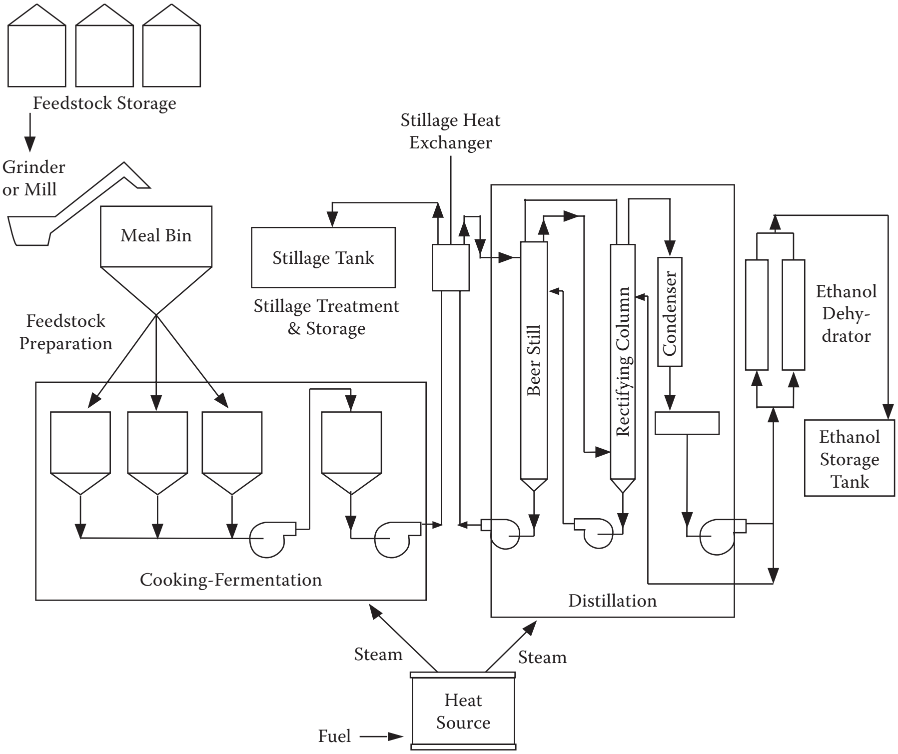


FIGURE 10.12 Diagram of ethanol production. Notice that heat for steam is needed in the process.

TABLE 10.6
Ethanol Yield from Crops

Crop	Liter/Ton	Liter/Ha/Yr
Sugar beet		7,000
Sugarcane	70	400–12,000
Corn	360	250–2,000
Sorghum		3,500
Cassava (roots)	180	500–4,000
Sweet potatoes	120	1,000–4,500

States, the number of ethanol plants (Figure 10.14) increased from 56 with a capacity of $7.3 * 10^6$ m^3/yr in 2000 to 170 plants with a capacity of $40 * 10^6$ m^3/yr at end of 2008. Most of the plants are concentrated in the upper Midwest (http://www.ethanolrfa.org/bio-refinery-locations). Remember that a gallon of ethanol has about two-thirds of the energy content of a gallon of gasoline, and what is sold is gasohol is a 10–20% mixture of ethanol and gasoline. Due to the economic crisis of 2008–2009, the construction of new ethanol plants has decreased, and some plants have been shut down or mothballed.

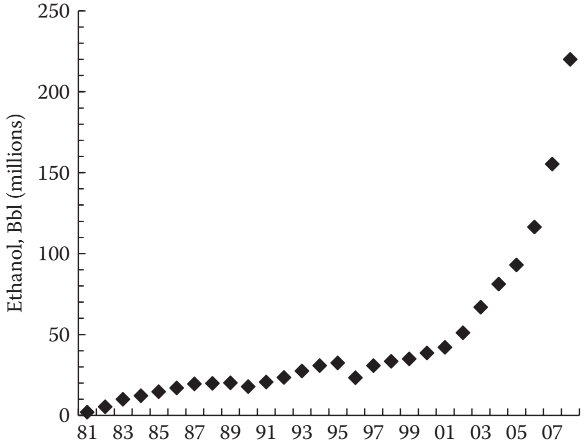


FIGURE 10.13 Ethanol production in the United States.

FIGURE 10.14 Ethanol plant near Herford, Texas.

10.4.2 BIODIESEL

Biodiesel can be produced from recycled vegetable oils, grease, and fat, and there is the possibility of dedicated fuel crops for biodiesel (Table 10.7), primarily palm oil and jatropha. World production of biodiesel was around 11 million tons, with biodiesel providing around 10% of diesel for transportation in Europe, with Germany the largest producer of biodiesel. Biodiesel from nonfood feedstocks is now part of national policies; for example, China set aside a large land area for growing jatropha and other nonfood plants for biodiesel, and India has up to 60 million hectares of nonarable land available for jatropha. Other countries are also pursuing programs for production of biodiesel from jatropha.

The United States produced over 16 million barrels of biodiesel in 2008, with 8.6 million barrels exported. Enough vegetable oil, soy oil, recycled restaurant grease, and other feedstocks are readily available in the United States to provide feedstock for about 40 million barrels/yr of biodiesel.

TABLE 10.7
Dedicated Crops for Biodiesel and Possible Annual Production

Crop	Liter/Ha/Yr
Palm	5,238
Jatropha	1,684
Castor	1,216
Canola	1,076
Sunflower	842
Soybean	561

10.4.3 BIOGAS

Biogas digesters use animal manure, sewage sludge, and liquid waste and convert it into gas and liquid fertilizer (Figure 10.15). A biogas digester should produce 200–400 m^3 of biogas with 50–70% methane per dry ton input, around 8 GJ per ton input. This is less than the energy content of dry dung or sewage; however, the process produces clean fuel and disposes of fragrant (smelly) waste. The temperature needs to be at least 35°C, so heat is required for biodigesters in cooler climates.

In the developing world, a large number of biogas digesters have been constructed: 7.5 million in China, 3 million in India, and over 37,000 biogas digesters installed from 1992 to 1998 in Nepal. In many developing countries, a biodigester is too costly for small farmers, and attempts to introduce community biogas digesters have faltered due to institutional problems. While solar power is excellent for lighting in rural areas, it is not well suited to providing energy for cooking. Traditionally, dung

FIGURE 10.15 Floating roof biodigester in South Africa. (Courtesy of Solar Engineering, South Africa.)

is burned directly as a fuel, or it is applied as a fertilizer to gardens. The processing of the cattle, or human, dung in a biogas digester provides both better quality gas and better fertilizer when compared with the raw manure product.

In the United States, there is a large amount of manure from confined animal feeding, from birds to pigs to cows. There was a plant to produce methane from manure near Guymon, Oklahoma; its name was Calorific Recovery by Anaerobic Processes, which gave them a great acronym. Presently in the United States, the primary commercial production of biogas is from landfills.

In the European Union, the total biogas production has increased from 3,000 tons of oil equivalent (toe) in 2004 to 5,901 toe in 2007, of which 2,905 toe were from landfill gas, 887 toe were from sewage sludge, and 2,108 toe were from other sources. Germany has the largest number of biogas plants, around 4,000.

10.4.4 MICROALGAE

Algae grow in aquatic environments and are classified as large, centimeter size, and are seen in ponds, with the largest example kelp in the sea. Microalgae are unicellar, micrometer in size, and grow in suspension in water. The advantages of using microalgae are rapid growth, high yield per land area, lack of sulfur in the biofuel produced, and nontoxicity and biodegradability. Some strains of microalgae have high levels, 25–55% by weight of lipids, of precursors for oil, and the theoretical production of biofuel is 75 m^3/ha/yr with realistic production levels of 4.5 to 7.5 m^3/ha/yr. Some algae can even produce hydrogen gas under specialized growth conditions. Around 4 million hectares (10 million acres) of land for algae installations would produce enough biodiesel to replace all the diesel currently consumed in the United States.

Algal biomass contains three main components: carbohydrates, proteins, and lipids/natural oils. Primary use of microalgae would be for biodiesel, with the possibility of using the residual mass for food, fertilizer, and even combustion for heat or electricity. Microalgae can double in size every 24 h and can regenerate in 48 to 72 h; cyanobacteria can regenerate in 5 to 20 h. These short generation times lead to the high potential for biodiesel production from algae.

Microalgae require three ingredients to grow: (1) high solar radiation, (2) carbon dioxide, and (3) brackish water or water high in salt content (up to 30,000 ppm). The logical location in the United States for growing algae under high levels of solar radiation would be the desert southwest.

Two possible systems for algae production [10] are raceway ponds and photo bioreactors. Raceway ponds provide for high production of algae and typically cost less per acre to construct; however, because they are open, they require control of contaminants and management of evaporation. Bioreactors are more costly to build per acre but can operate year round because they are enclosed, typically in glass or film tubes. After generation and production of lipids in the algae, the algae must be harvested, concentrated, and converted to fuel. Harvesting processes include processes such as pumping the algae to settling tanks and using rakes or skimmers [11].

The lipid/algae water slurry must go through an oil separation and purification process. Chemical extraction and mechanical extraction are the primary methods for oil separation. Hexane is used successfully in separation applications but may be cost prohibitive. Centrifuge processes have also been successful but require high-energy inputs for large-scale production. Research is under way to develop high-capacity separation technologies. Algae production as a dedicated biodiesel feedstock is now an area of extensive research as academia, private industry, and governmental agencies are investigating microalgae in terms of processes to get to commercial operation. Major energy companies, even Exxon-Mobil, are now pursuing research and development, and there are a number of pilot projects. Theoretically, algae could supply the entire U.S. diesel demand from 1 million hectares of land with high-saline groundwater sources and from locations where traditional field crops cannot be planted. It is not surprising that the U.S. Department of Defense is interested in the production of jet fuel from algae.

PetroSun planned a commercial microalgae facility in Rio Hondo, Texas, to produce an estimated $1.2 * 10^4$ m^3 of algal oil and 50 million kg of biomass per year from a series of saltwater ponds spanning 440 ha. Two of those hectares would be reserved for the experimental production of a renewable JP8 jet fuel. With the economic crisis of 2008, the project was placed on hold.

Example 10.2

This example concerns the pilot project, Texas AgrilLife Research and General Atomics, located at Texas AgrilLife Research Station, 10 miles west of Pecos. The Permian basin (site of the pilot project) has superior characteristics for algae production: available nonarable land, high solar radiation, brackish water, and geologic carbon dioxide. There are two independent sets of ponds (Figure 10.16). Each set consists of four ponds that represent a step in the growing process. Each pond system includes

Four medium raceways, bathtub size (Figure 10.17)
One 3.8-m^3 raceway (Figure 10.18)
Two 7.6-m^3 raceways
One 22.7-m^3 raceway
Four settling tanks

Algae are started in photobioreactors in the on-site laboratory and then moved from small to large raceways as density increases.

Example 10.3

Solix has a pilot-scale photobioreactor (Figure 10.19) located near Durango, Colorado, on the Southern Ute Indian Reservation. Each panel in the basin is 36.6 m long and contains approximately 680 L of algal culture. There are 120 panels per basin with a capacity of approximately 82,000 L of algal culture, and there are three basins. Typically, growth rates at this location exceed 0.2 g/L per day during the growing season.

FIGURE 10.16 Algae production pilot project, Pecos, Texas. Photo at early stage since raceway ponds are not green. (Courtesy of Texas AgriLife Research, Texas A&M System.)

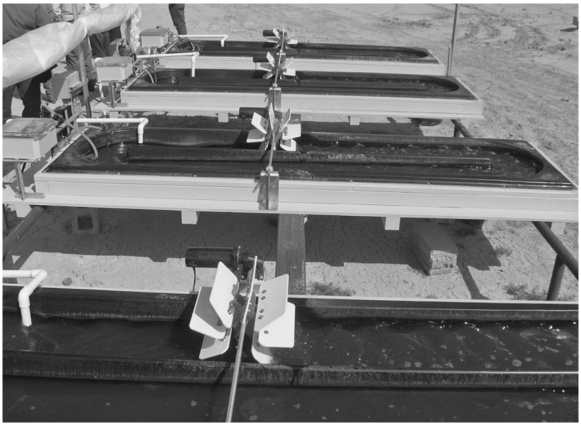


FIGURE 10.17 Medium raceways. (Courtesy of Texas AgriLife Research, Texas A&M System.)

FIGURE 10.18 Next size raceway, 3.8 m^3.

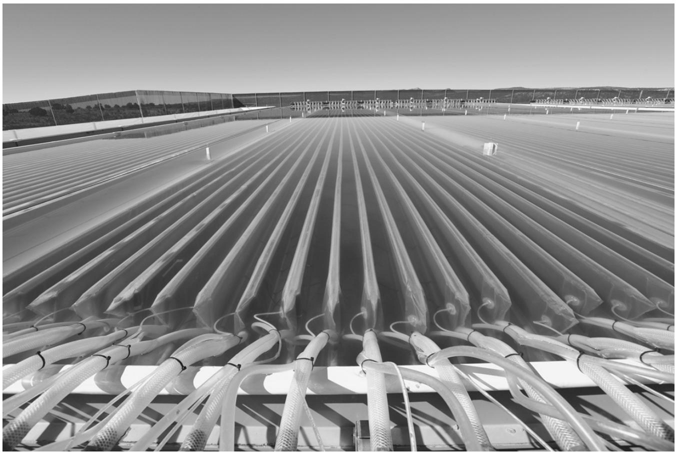


FIGURE 10.19 Photobioreactor for algae production. (Photo © Copyright Solix Biofuels Inc.)

10.5 COMMENTS

The manipulation of bacteria and algae for the production of bioenergy and other products will have a significant impact on the future production of liquid fuels. The problem is still the same as most other renewable energy resources: low density, initial high cost, and the logistics of transportation of biomass and end product. However, biofuels solve the problem of storage and logistics as distribution is already in place, and biofuels can also be used for power plants. Primary research areas are the use of cellulose rather than sugars for producing ethanol, bacteria for production of methane and hydrogen, and algae for production of biodiesel. Of course, commercial operations are seeking to improve the efficiency of their bioenergy operations.

The use of bioenergy for electricity and biofuels will increase in both developed and underdeveloped countries. In developed countries, electricity growth will be from landfill gas, MSW combustion, and wood and animal wastes. How much electricity would be from energy crops will primarily be dependent on tree farms. Even though there may be a shift from bioenergy in developing countries, the use of bioenergy will grow due to population growth. Therefore, bioenergy will remain the main domestic source for these countries. Also, there is not much land that could be shifted from food and fiber to bioenergy production. However, with the use of nonproductive land for farming, bioenergy could increase from today's 40 to 60 EJ/yr to 100 to 200 EJ/yr. The largest estimates are near 280 EJ/yr by 2050 due to the large increase in biofuels.

The switch of productive land from cultivation of food crops to feedstock for bioenergy would be a problem. How much land will be taken out of production per megawatt capacity for the following systems: trough collector, PV, wind, or bioenergy (corn)? Of course, use of nonproductive cropland for bioenergy would be positive.

Besides food and fiber, the agricultural industry is now entering the energy industry. There have been economies of scale for wind farms and ethanol plants (Figure 10.19); however, there is the possibility to have modular bioenergy systems for farms and ranches, which not only would provide energy for the farm and ranch but also would provide excess energy to sell. A small-scale energy system could combine wind, PV, and biomass and the farmer would be self-sufficient and could even sell excess energy not used at the farm.

Again, energetics has to be considered for bioenergy systems. The terms *energy balance*, *energy payback ratio*, or *energy ratio* are also used. Energetics is the calculation of the energy content of the end product compared to the total energy input to produce that product. If the energetics is small, that energy system should be carefully scrutinized, especially if it receives economic subsidies. Again, it does not matter what the economics (dollars) are because in the final analysis physical laws triumph.

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RECOMMENDED RESOURCES

LINKS

American Bioenergy Association. http://www.biomass.org/.

Annual industry outlook, previous years and 2009. http://www.ethanolrfa.org/objects/pdf/outlook/RFA_Outlook_2009.pdf.

Biomass Combined Heat and Power Partnership. http://www.epa.gov/chp/basic/renewable.html.

Biomass energy data book. 2nd ed. http://cta.ornl.gov/bedb/index.shtml.

Biomass Power Association. http://www.usabiomass.org.

Cultivation in photoreactor. http://www.oilgae.com/algae/cult/pbr/pbr.html.

Department of Energy. Energy efficiency and renewable energy, biomass program. http://www1.eere.energy.gov/biomass/.

European Biomass Association. http://www.aebiom.org.
Google images. Many photos of dung for fuel are available.
International Energy Agency. FAQ on biogas. http://www.sgc.se/biogasfaq/.
Landfill gas, project development handbook. http://www.epa.gov/landfill/publications-tools/handbook.html.
P. J. Leman. CHP and biopower: market drivers and outlook, 2008. http://www.epa.gov/chp/documents/meeting_52508_lemar.pdf.
List of commercial scale anaerobic digestion plants, world. http://www.iea-biogas.net/anlagelisten/Plantlist_08.pdf.
National Biodiesel Board. http://www.biodiesel.org.
National Renewable Energy Laboratory. http://www.nrel.gov/biomass/.
Oilgae, algae energy. http://www.oilgae.com.
Renewable Fuels Association. http://www.ethanolrfa.org. Also has a map of ethanol plant locations.
U.S. biomass R&D. http://www.brdisolutions.com/default.aspx.
U.S. Energy Information Administration. Renewable and alternative fuels. http://www.eia.doe.gov/fuelrenewable.html.
U.N. Food and Agricultural Organization. http://www.fao.org.stastitics.
U.S. Department of Energy. 2008. World biofuels production potential. http://www.pi.energy.gov/documents/20080915_WorldBiofuelsProductionPotential.pdf.

PROBLEMS

1. OM (order of magnitude): Estimate the mass for humans on the Earth. Estimate amount of energy humans need in food per year.
2. OM: Estimate total annual production for the world in terms of mass and energy from major food crops: corn, wheat, and rice.
3. What is average conversion efficiency of photosynthesis?
4. OM: For cultivated crops, use 1 ha of land. On an annual basis, what is the solar input, and what is the output? Be sure to state region and insolation (solar input) for your crop.
5. How is charcoal made? Why do people use charcoal for cooking and heating rather than wood?
6. Compare the energy content of very dry wood to coal; use units of energy/mass.
7. For your country, what percentage of the energy is derived from wood or wood products? Be sure to state the country and where you obtained data (year).
8. What are the possible energy products from MSW?
9. Find the nearest landfill to your hometown. List the town and location. Is the methane vented or used? If used, if possible state how much is generated per year and what its uses are.
10. Why did ethanol production in the United States increase significantly?
11. Find the location of the nearest ethanol plant to your hometown. State the location and capacity.
12. OM: What is the energetics for producing ethanol from corn, which is irrigated from wells 80 m deep? Average rainfall is 50 cm/yr.
13. How many CHP plants from WWTFs are there in the United States?

14. What is the typical size range (power) of CHP plants at WWTFs in the United States?
15. What two countries in the European Union use the most biodiesel?
16. If you live in the United States, pick any other country in the world that uses biogas. Give and estimate of amount and use.
17. In China and India, what is the primary use for biogas?
18. Why is a there a large research interest in microalgae?
19. List two advantages and two disadvantages for using microalgae to produce biodiesel.
20. What was the approximate world biofuel production in 2010? Make an estimate for 2020 and 2030 and give reasons for your answer.
21. OM: Suppose you wanted to supply 50% of the U.S. demand for gasoline with ethanol from corn. Approximately how many hectares would be needed? 1 ha = 2.5 acres.
22. OM: Suppose you want to supply 50% of the U.S. demand for diesel with biodiesel from algae. Approximately how many hectares would be needed? Be sure to state how much diesel per year is used in the United States.
23. OM: Suppose you want to supply 50% of the world demand for diesel with biodiesel from algae. Approximately how many hectares would be needed? Be sure to state how much diesel per year is used in the world.
24. OM: Suppose India wants to supply 80% of its demand for fuel for transportation from jatropha. Approximately how many hectares would be needed?
25. The goal of 25% energy from bioenergy by 2025 for the United States would require approximately what amount of resources by type?
26. Compare the two methods of algae production: open ponds and photoreactors.
27. OM: The U.S. military is interested in biodiesel from algae. Approximately how many hectares would be needed to supply that demand? Be sure to state how much diesel per year is used.

11 Geothermal Energy

11.1 INTRODUCTION

The temperature gradient in the crust of the Earth is 17–30°C per kilometer of depth. For example, deep mines are hot, and most need cooling for the miners. Plumes of magma ascend by buoyancy and force themselves into the crust, generally along the edges of tectonic plates (Figure 11.1), which results in volcanoes. There are huge regions of subsurface hot rocks with cracks and faults that allow water to seep into the reservoir, which then results in hot springs, geysers, mud pots, and fumaroles. Two famous examples are Yellowstone Park and Iceland, which is an exposed section of the Mid-Atlantic Ridge.

Geothermal energy is not renewable in the same sense as solar, wind, and hydro energy, and the average heat flow of the Earth is a thousand times less than the low-density solar insolation. Another major difference is that solar and wind energy are variable on short time periods, and hydro is variable by season; however, geothermal energy only declines as heat is taken out, with lifetimes of 100 or more years. Even though the heat flow is small, there are many locations in the world with reservoirs of hot rock with water and steam that can be used for heat and for the generation of electricity. These regions have average heat flow around 300 mW/m^2 compared with a

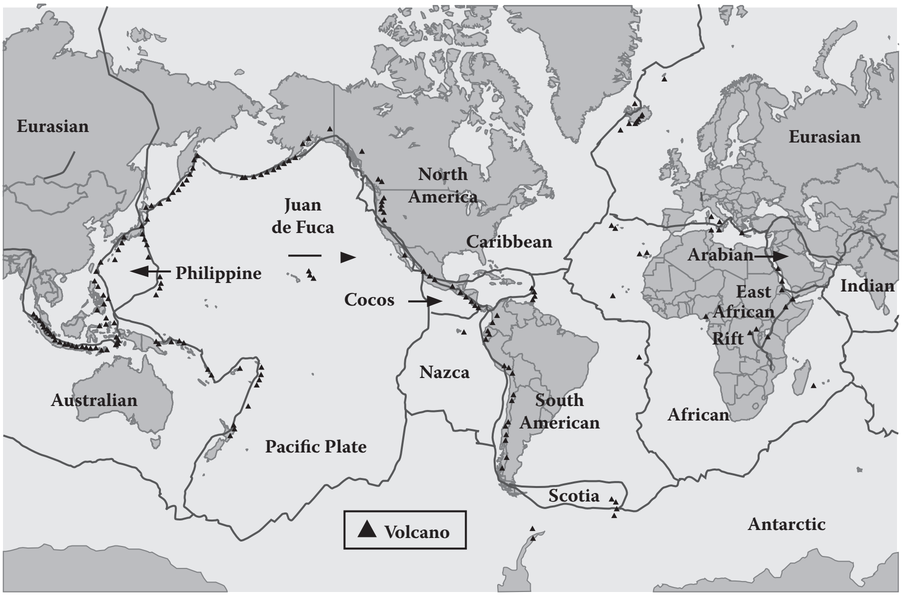


FIGURE 11.1 Tectonic plates of the Earth with volcanoes (historical).

global average of 60 mW/m^2. In the generation of electricity, the heat flow of the Earth is much less than the removal of energy from the hot rock reservoirs, so it is similar to mining. But the geothermal reservoirs are large, and they will produce energy for years.

The heat content per unit mass is a function of pressure, volume, and temperature; reservoirs are classified according to temperature: high (water and steam at temperatures of 182°C and above); medium, 100–182°C; and low, less than 100°C (essentially no steam). Around 77 TWh of electricity was generated from geothermal energy in 2009 from an installed capacity of around 11,300 MW. In addition, the amount of thermal energy for direct use is around double the electrical energy.

With reservoir temperatures of 120–370°C, hot water or steam can be used to generate electricity in a conventional power plant. Hot water that is trapped in underground reservoirs within 1 to 6 km of the surface can be tapped by drilling. Enhanced geothermal systems (EGSs) are hot rock reservoirs that have to be modified by hydraulic fracturing because they have low permeability and porosity. There is also renewed interest in the energy potential of geopressure-geothermal resources and the geothermal fluids found in oil and gas production fields as well as some mining operations.

Shallow reservoirs of lower temperature, 20–150°C, are used for space heating, greenhouses, aquaculture, industry, and health spas. The macaques of northern Japan use hot springs for warmth in the winter (for some great photos, go to Google images, http://www.google.com/imghp). Geothermal heat pumps (GHPs) use an electric heat pump to exchange heat with the ground or groundwater, instead of air, and can be used in almost all areas of the world. These systems for residences and larger buildings are now competing with conventional heating and cooling systems.

11.2 RESOURCE

The geothermal resource for direct use and the generation of electricity is located along the tectonic plate boundaries and magma plumes, such as in Hawaii and Yellowstone [1]. The size of the resource (Table 11.1) could supply all the primary energy for heat and electricity for the world. However, use is restricted due to location in relation to population, and of course, it is also restricted by economics. The total

TABLE 11.1
Geothermal Energy Resource Base for World and the United States

Regime	World Continental, 10^9 BOE	United States, 10^9 BOE
Magma systems	2,400,000	160,000
Crustal heat	79,000,000	2,300,000
Thermal aquifers	130	9

Source: From Geothermal energy, www.geothermal.org/GeoEnergy.pdf.
BOE = barrel of oil equivalent.

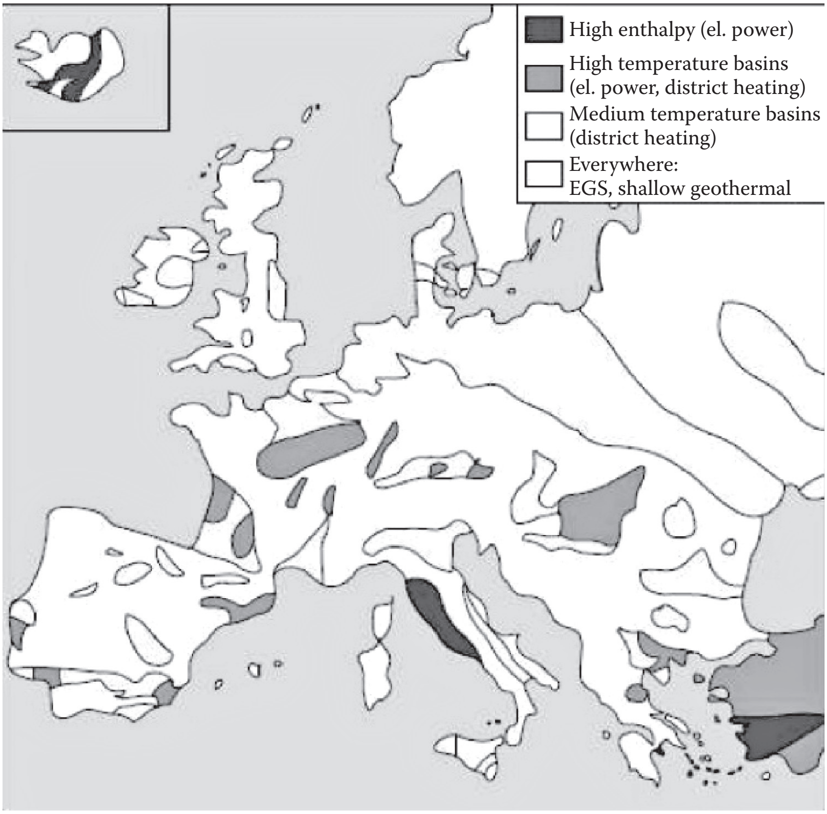


FIGURE 11.2 Geothermal map for Europe. Inset is Iceland. (Map from European Geothermal Association.)

stored heat energy up to a depth of 5 km worldwide is estimated at 1.5 * 10^{26} J, and if 1% can be mined, the recoverable resource is on the order of 1.5 * 10^{24} J.

Regions and nations along the boundaries of the tectonic plates are using geothermal energy and have maps of the resource. In Europe (Figure 11.2), Italy, Iceland, and Turkey are the major areas. Iceland, with an area of 103,000 km^2 (Figure 11.3), has a geothermal resource estimated at 96,800 EJ within 3 km of the surface, and the technically capturable energy is 3,320 EJ, which at their current energy consumption would last for 40,000 yr.

In the United States, the resource is primarily in the west (Figure 11.4). There are 271 cities and communities with a population of 7.4 million in the 10 western states that could potentially utilize geothermal energy for district heating and other applications.

Information for regional and national geothermal resources is available in the Recommended Resources section of this chapter.

A good site for geothermal use is that of the International Geothermal Association ("Geothermal in the World"), available at http://www.geothermal-energy.org/105,interactive_map.html. The data may be a few years old but are indicative of use by country.

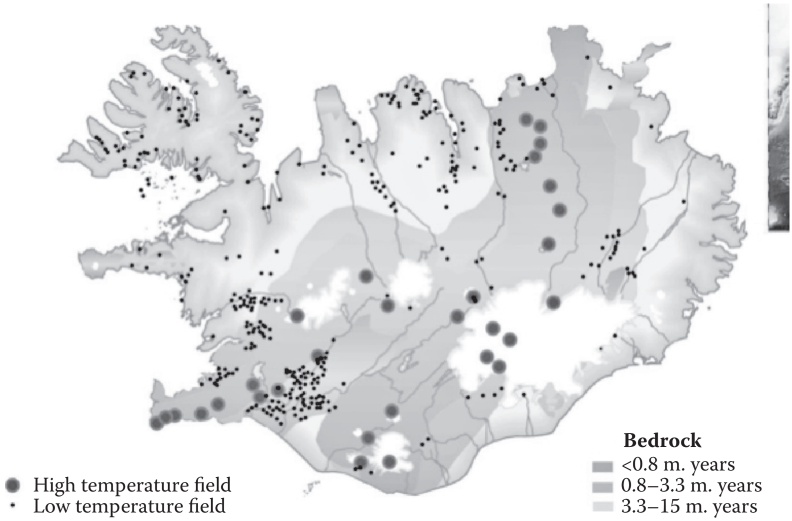


FIGURE 11.3 Geothermal map for Iceland showing high- and low-temperature fields.

11.3 TYPES OF GEOTHERMAL RESOURCES

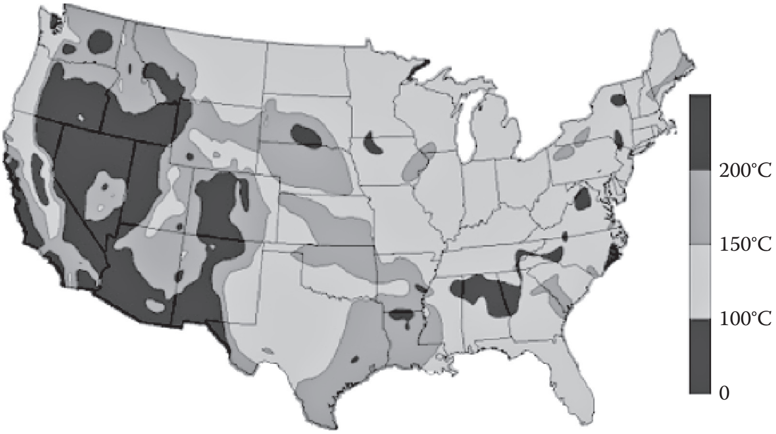
The types of geothermal resources are convective hydrothermal systems; EGSs; conductive sedimentary systems; coproduction, with water from oil and gas fields; geopressure systems; and magma energy.

The convective hydrothermal system is a heat reservoir that has high enough permeability and porosity for the convection of water. The reservoir has a nonpermeable rock layer to retain the heat but enough fractures for recharge (Figure 11.5). Surface indications of such reservoirs are hot springs, geysers, and the like, and the reservoirs may or may not be associated with volcanoes. There is a limited distribution of these worldwide; however, they have been used throughout history and have been exploited for direct use and the generation of electricity. Estimated reserves in the United States are 10,000 to 30,000 MW [2].

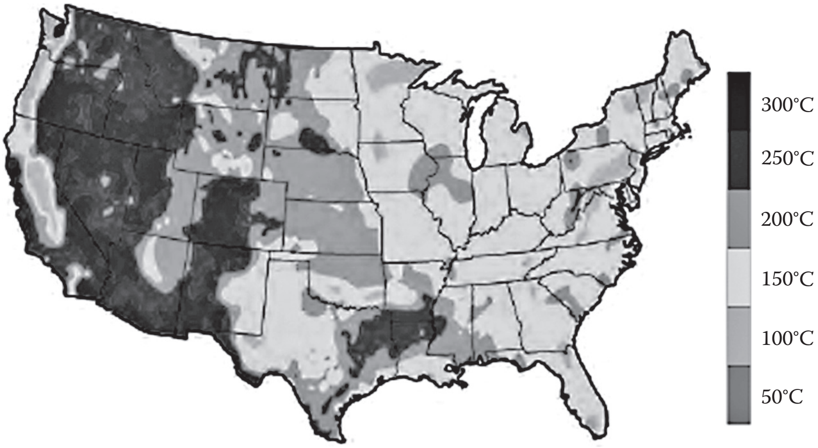
Regions for EGSs are found worldwide and feature hot conductive rock with low permeability and porosity. EGSs are still at the experimental or prototype stage. Boreholes to check the thermal gradient (Figure 11.6) have to be drilled, and then production and injection wells have to be drilled and the formation fractured (Figure 11.7) with the same techniques used for oil and gas production. The primary challenges are creating a large fractured rock volume, providing enough flow for commercial production, minimizing cooling, and minimizing water loss. The main constraint is creating sufficient connectivity within the stimulated region of the EGS reservoir to allow for high production rates without reducing reservoir life by too rapid cooling.

Conductive sedimentary systems have basins with high heat flow, and in general fracturing would be required. However, the resource is deep, so drilling costs will be high; at present, there are no commercial systems.

Coproduction of geothermal energy from oil and gas fields is a possibility. Some areas of oil and gas development have relatively high temperatures; for example,



(a)

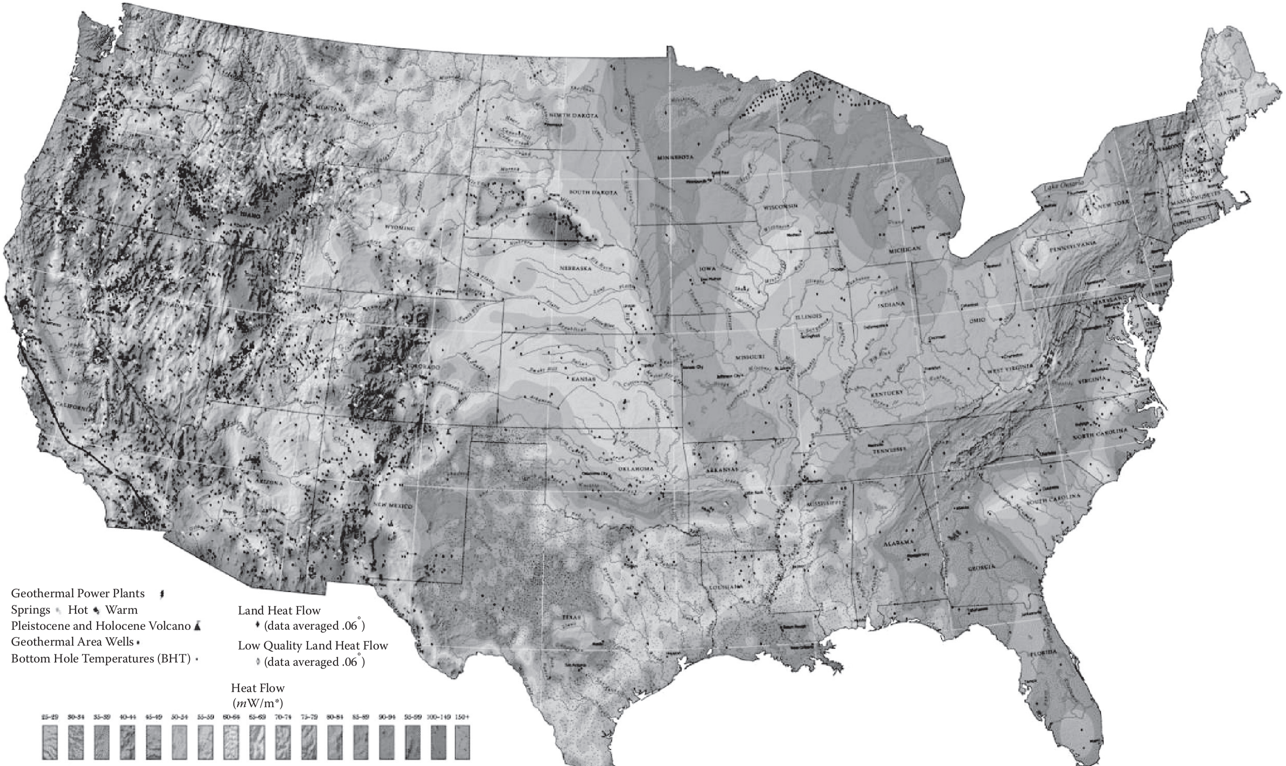


(b)

FIGURE 11.4 (a) Geothermal map for the United States, depth 6 km (from EERE, DOE); (b) geothermal resource map for enhanced geothermal systems for the United States, depth 10 km (map from Geothermal Energy Association. March 2009).

parts of east and south Texas and northwest Louisiana are characterized by temperatures of 150–200°C at depths of 4 to 6 km. In addition to temperature requirements, a geothermal project requires large-volume flows of water, about 4 m^3/min per megawatt (depending on the temperature).

Many oil and gas wells in the United States are stripper wells, defined by production of oil less than 10 bbl/day and gas less than 2,100 m^3/day. In some wells, the ratio of water to oil is higher than 10/1. Also, water flooding is a common technique for secondary recovery in old oil fields. In Texas and Oklahoma, the water production from oil fields is over 8,000 m^3/min. There is the expense of disposal of this saltwater, primarily by reinjection. At an average temperature of 150°C, that would



SMU Geothermal Lab, Geothermal Map of United States, 2004

(c)

FIGURE 11.4 (continued) (c) heat flow map for the United States (from Southern Methodist University).

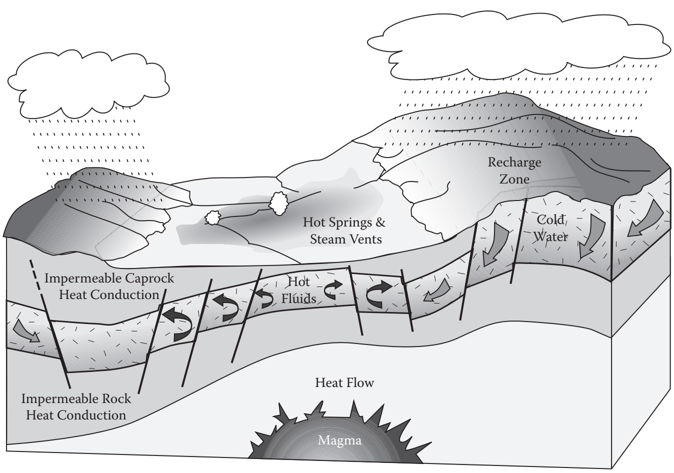


FIGURE 11.5 Hydrothermal hot reservoir.

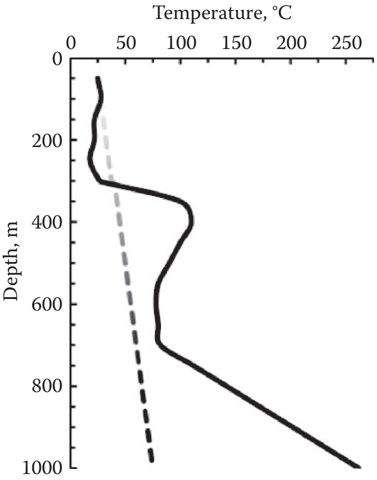


FIGURE 11.6 Thermal gradient in a borehole in geothermal area compared to typical linear gradient.

be an equivalent power of 8,000 MW. In general, these oil fields are not close to load centers, so the geothermal energy has never been used.

For depleted oil fields where subsurface temperatures are high enough, the wells could be converted to produce hot water instead of capping them, but the cost of the hot water would still be high due to pumping costs. One demonstration project is online in Wyoming, and one is planned for Florida [3]. The Rocky Mountain Oil Test Center (http://www.rmotc.doe.gov/index.html) is a demonstration project near Casper, Wyoming. In August 2008, a 250-kW Ormat organic Rankine cycle (ORC) power unit was installed, and as of February 2009, the unit had produced 590 MWh of power from 3 million barrels of hot water.

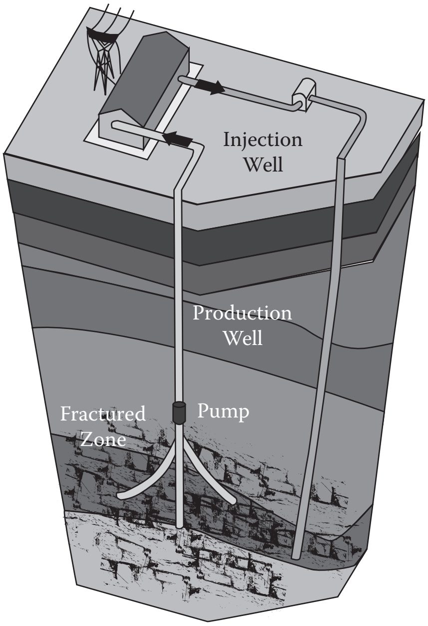


FIGURE 11.7 Enhanced geothermal system from formation that has been hydraulic fractured.

A proposed demonstration project at the Jay Oil Field, Florida, would have a capacity of 200 kW, but there is the potential for 1 MW. The daily production capacity is around 4,500 bbl of crude oil and 5–7 million ft^3 of natural gas. Overall, hot water represents approximately 95% of the fluid stream as 120,000 bbl per day at approximately 90°C are pumped and reinjected into the field. Quantum Resources, the operator, shut the field down in 2009 but reopened the field after securing tax breaks from the state. If the geothermal project makes it to the commercial stage, it would extend the production of oil and gas and provide energy and jobs.

For small producers, use of geothermal energy could reduce the cost of pumping the fluid. A demonstration project installed a 30-kW unit on an oil well (2,900 m deep), which pumped 100 bbl oil and 4,000 bbl of water per day from a water flood field. The waste heat unit is expected to pay about one-third of the pumping costs with a payback of 3–4 yr as it would replaced electric energy at $0.098/kWh for pumping.

Geopressure systems have reservoir pressures higher than hydrostatic pressure; however, they have limited distribution. In addition to thermal energy, there is kinetic energy and energy from methane. There is a large geopressure basin that runs along the Gulf Coast of the United States from the Mexican border to Mississippi with a geothermal resource of 46,000 EJ [3], and that does not count the energy in the natural gas (methane). To date, there are no commercial projects, although the geopressure characteristics have been studied extensively, wells were drilled, and there has been a feasibility project. From late 1989 until early 1990, a 1-MWe (megawatt electric) plant was operated on the Pleasant Bayou near Houston, Texas, from a well that produced hot water and natural gas. About half of the power was

TABLE 11.2
Estimated Geothermal Resource by Type in the United States

Type	Resource to 10 km, EJ
Convective	$2.4–9.6 * 10^{21}$
Enhanced geothermal	$1.4 * 10^{25}$
Conductive	$1 * 10^{23}$
Oil/gas field water	$1.0–4.5 * 10^{17}$
Geopressure	$0.7–1.7 * 10^{23}$
Magma energy	$7.4 * 10^{22}$

generated by a binary cycle plant and about half by a gas engine with a generator. The plant only operated for 6 months because of economics, primarily due to the low price of natural gas at that time. The well was flow tested for about 5 yr with limited drawdown, so the reservoir is sufficiently large to sustain production for many years. There are several technical challenges for recovering geopressure energy.

Magma energy is localized, and there are many technical challenges.

The United States geothermal resource has been estimated for the different types (Table 11.2). Also, the report [4] shows resource maps for different depths below the surface.

The hydraulic power (m^3-m/time) is determined by the volume pumped and the dynamic head. The amount of power in the fluid is calculated from the mass flow, the enthalpy (energy/mass) at the input and output temperatures. Values for enthalpy are obtained from tables.

$$P = (m/t) * (Eh1 - Eh2) \tag{11.1}$$

where P is power, m/t is the mass flow (kg/s), Eh1 is the enthalpy at the wellhead (heat/mass of saturated liquid, temperature 1, degrees kelvin), and Eh2 is the enthalpy at the output (heat/mass of saturated liquid, temperature 2, degrees kelvin.

Example 11.1

A well produces the following: m/t = 32 kg/s, Eh1 = 377 kJ/kg (90°C), Eh2 = 209 kJ/kg (50°C).

$$P = 32 \text{ kg/s} * (377 - 209) \text{ KJ/kg} = 5{,}380 \text{ KJ/s} = 5.4 \text{ MWt (megawatts thermal)}$$

Because of the confidence level for fluid production, use 0.75, then P = 4.0 MWt per well.

If you have to pump the fluid to the surface, then that energy has to be subtracted from energy obtained in the fluid. The production for a geothermal field can be estimated [5] for the load data and use, especially peak demand. As noted, the design engineer should have a fairly good idea of the characteristics of the reservoir.

11.4 DIRECT USE

The direct use of geothermal energy in the world is estimated at 32,000–40,000 MWt; however, the contribution of shallow reservoirs, especially for bathing, spas, local space heating, and other small installations, is more difficult to estimate. The main direct uses are for space heating [6,7], bathing, and swimming. For the different applications, capacity factors are estimated at 15–72%. The leading countries for direct use are China, Sweden, the United States, Iceland, and Turkey. In Iceland, direct use of geothermal energy is around 1,844 MWt, and 90% of the homes are heated by geothermal hot water. Direct use in Europe is estimated at 14,140 MWt, and the major countries making direct use are Sweden (3,840 MWt); Turkey (1,385 MWt), primarily for district heating and swimming pools and spas; and Germany (952 MWt) [6, 2007 data]. The main use of geothermal energy in Hungary is for direct use with a production rate of 120 million m^3/yr. However, due to the high production, the hydraulic head has decreased 50–70 m, so now reinjection is required. Direct use in China is over 2,000 MWt. Current U.S. installed capacity of direct use systems is around 650 MWt.

Bathing, spas, and local space heating are generally from hot springs, so no external energy may be needed to move the hot water. For other direct use systems, a well is drilled into the reservoir, and there are pumps to bring the hot water to the surface. Then, there are heat exchangers, pipes for distribution, controls, and a disposal system, either on the surface or reinjected (Figure 11.8). Surface disposal means that water quality standards must be met. Standard equipment is used in most direct use systems, with allowances for water quality and temperature as corrosion and scaling may lead to problems. Atmospheric oxygen must be prevented from entering energy district heating waters, which can be accomplished by heat exchangers. A peaking system may be necessary to meet maximum load, which can be a parallel source of energy or tank storage.

An interactive map of U.S. direct use projects is available (http://geoheat.oit.edu/dusys.htm). Twenty-one case studies for the United States are available from the Geo-Heat Center, Oregon Institute of Technology (http://geoheat.oit.edu/casestudies.htm).

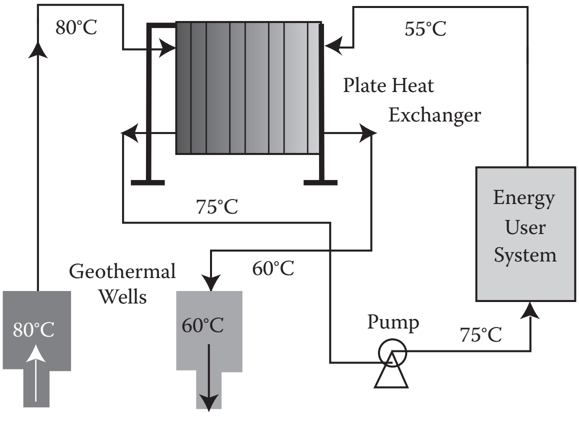


FIGURE 11.8 Diagram of direct use geothermal system with heat exchanger.

11.4.1 SPRINGS, SPACE HEATING, OTHER

The earliest use of natural hot springs was for bathing and cooking; today, resorts, swimming pools, and space heat are still major users of direct heat. Besides space heating for homes, the use of geothermal energy expanded into other areas: greenhouses, aquaculture, drying of agriculture products and lumber, desalinization, industrial processes that require heat, heated sidewalks, and even cooling.

There have been a few cases for which tubes are placed in the ground, and air is circulated through the tubes for heating and cooling. The problem is that a large mass of air needs to be circulated, and the heat exchange area with the ground also needs to be large.

11.4.2 DISTRICT HEATING

District heating is used in a number of places in the world. Turkey uses 493 MWt for district heating [8], and there are a number of district heating utilities in Europe [9–11]:

France: 38 plants in the Paris region, others in Aquitaine
Italy: Po-plain (Ferrara), Tuscany
Germany: Northern Germany (e.g., Waren, Neustadt-Glewe), Munich area (e.g., Erding, Unterschleissheim, Pullach)
Poland: Northern Poland (e.g., Pyrcyze), Tatra foothills (Zakopane)
Austria: North and south of the Alps (e.g., Altheim, Bad Blumau)
Hungary: All the Pannonian basin (e.g., Hódmezövásárhely, Kistelek)
Others: Denmark (Thisted, Copenhagen), Sweden (Lund, Malmö), Lithuania (Klaipeda)

The district heating utility in Reykjavík, capital of Iceland, is the largest in the world, as geothermal energy is used to heat the entire city and five neighboring communities. The geothermal power is about 780 MWt, and 60 million m^3/yr of hot water flow through the distribution system. Two of the low-temperature fields are located within the city limits, and the other two (high temperature) are 20 km northeast of Reykjavík. Initially, only the flow from springs and relatively shallow artesian wells was used, but in the 1960s and early 1970s, production wells were drilled in all the fields, and down-hole pumps were installed to increase the flow. Pumping in the low-temperature fields lowered the water level, and surface springs disappeared. By increasing water from the high-temperature fields, it was possible to reduce the pumping from the low-temperature fields, and the water level increased. About 70% of the energy used for district heating comes from the low-temperature fields; the rest is from the high-temperature fields. The water from the low-temperature fields is used directly for heating and tap water. Due to a high content of gases and minerals at the high-temperature fields, water and steam are used to heat freshwater. From 1998, electricity has been cogenerated from geothermal steam at another field.

The largest direct heating district in the United States is in Boise, Idaho [12]. The district supplies heat to over 55 businesses in the downtown area, primarily space heating, but the supply also includes hot water for recreation, greenhouses, and aquaculture. Now, 100% of the water is injected back into the aquifer.

The Oregon Institute of Technology campus in Klamath Falls has a district heating system. Since 1964, the campus has been heated by geothermal hot water from three wells. The combined capacity is 62 L/s of 89°C water, with an average heat utilization rate of 0.53 MWt and a peak rate of 5.6 MWt. In addition to heating, a portion of the campus is cooled using an absorption chiller powered by geothermal hot water. The chiller requires a flow of 38 L/s and produces 541 kW of cooling capacity with 23 L/s of chilled water at 7°C. Plate heat exchangers have been installed in all buildings to isolate exposure to the geothermal fluids.

Case Studies

1. “Years of Direct Use–District Heating Riehen,” http://www.iea-gia.org/documents/SiddiqiRiehenNZSustainWorkshop10Nov08.pdf.
2. Canton Basle-City, northwest Switzerland. Temperature 62°C, injection temperature 29°C, production rate about 72 m^3/h.
3. In Klamath Falls, Oregon, there are over 550 geothermal wells serving a wide variety of uses. There is a city district heating system (8.5 MWt at 99°C) and snow melt systems (1.2 MWt at 99°C) for sidewalks. See "Geothermal in Oregon, Where It Is Being Used," http://www.oregon.gov/ENERGY/RENEW/docs/tp124.pdf.

11.5 GEOTHERMAL HEAT PUMPS

The installation of GHPs has been growing rapidly across the developed world. GHPs can be used in almost all locations around the world. Since the ground temperature is fairly constant, around 10°C at 5 m depth, the ground can be used as a reservoir for heating and cooling with heat pumps, with heat taken out in the winter and injected in the summer. The types of GHPs are ground or ground source, groundwater source, and water source. Sometimes, the systems are referred to as geoexchange systems. The system can be a closed loop with boreholes, lateral bed, and ponds and lakes as the reservoir (Figure 11.9) and open loop (Figure 11.10) from an existing water source with recharge or disposal. Heat pumps that use air as a reservoir have auxiliary resistance heating during freezing weather, so GHPs are more efficient.

The open-loop system uses well or surface body water as the heat exchange fluid that circulates directly through the GHP system. Once it has circulated through the system, the water is returned through the well, a recharge well, or surface discharge. This option is only practical if there is an adequate supply of relatively clean water, and all local codes and regulations regarding groundwater discharge are met.

Which system is used depends on climate, soil conditions, available land, and installed costs. The composition and properties of the soil and rock (which can affect

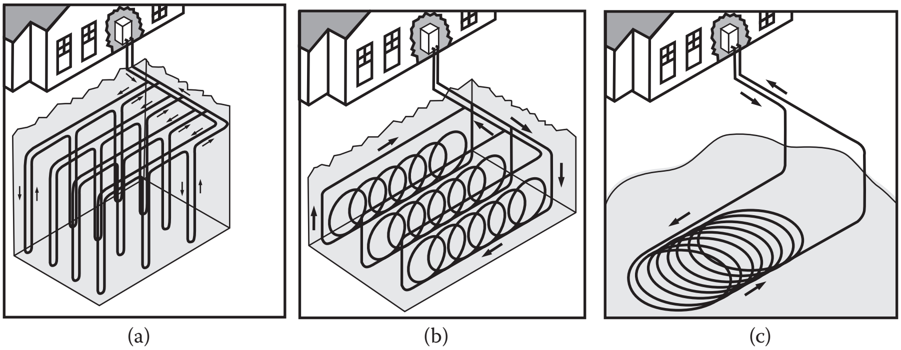

(a) (b) (c)

FIGURE 11.9 Geothermal heat pump, closed-loop systems; (a) borehole, (b) lateral, and (c) pond/lake.

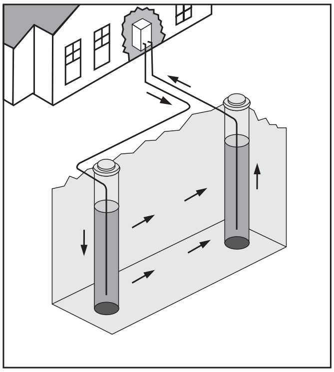


FIGURE 11.10 Geothermal heat pump, open-loop system.

heat transfer rates) affect the design as soil with good heat transfer properties requires less pipe. Also, the local conditions will determine whether lateral (Figure 11.11) or boreholes are used. Ground- or surface water availability (depth, volume, and water quality for open-loop systems) also plays a part in deciding what type of ground loop to use. Before an open-loop system is installed, be sure the hydrology of the site is known, so potential problems such as aquifer depletion and groundwater contamination can be avoided. Antifreeze fluids circulated through closed-loop systems generally pose little to no environmental hazard.

The amount and layout of the location of underground utilities or sprinkler systems also have to be considered in system design. Horizontal ground loops (generally the most economical) are typically used for newly constructed buildings with sufficient land. Vertical installations or slinky installations are often used for existing buildings because they minimize the disturbance to the landscape.

The biggest benefit of GHPs is that they use 25–50% less electricity than conventional heating or cooling systems. GHPs can reduce energy consumption up to 44% compared to air-source heat pumps and up to 72% compared to electric resistance heating or conventional heating/cooling systems.

(a)

(b)

FIGURE 11.11 Examples of closed-loop system, (a) lateral with vertical slinky (courtesy of Virginia Tech) and (b) lateral with horizontal slinky (courtesy of Air Solutions).

The heating efficiency of heat pumps is indicated by their coefficient of performance (COP), which is the ratio of heat provided per energy input. The cooling efficiency is indicated by the energy efficiency ratio (EER), which is the ratio of the heat removed to the energy input. Units should have a COP of 2.8 or greater and an EER of 13 or greater.

In the United States, over 1 million GHPs have been installed as the Energy Information Administration provides data on number of GHPs shipped (Figure 11.12) by type: ARI-320 (water source), ARI-325/330 (groundwater and ground source), ARI-870 (direct geoexchange), and other non-ARI (Figure 11.13). GHPs have a major impact on direct use in the United States as GHPs provide more energy than

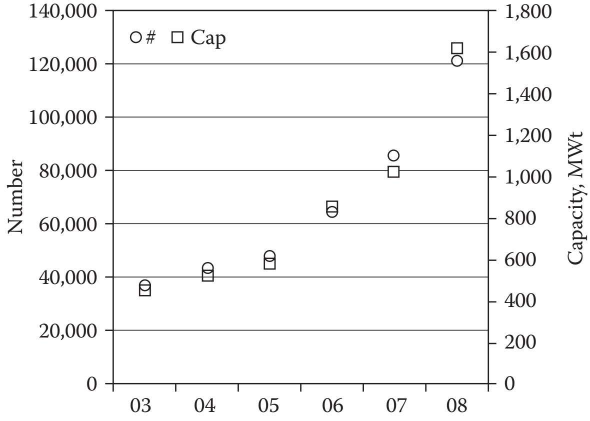


FIGURE 11.12 Number of geothermal heat pumps in the United States, shipped and capacity.

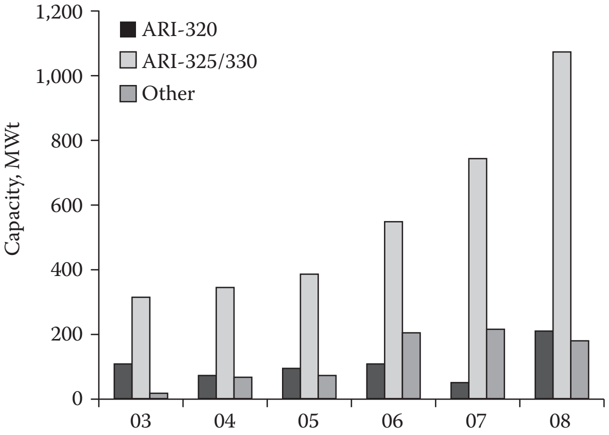


FIGURE 11.13 Capacity of geothermal heat pumps in the United States, shipped by type.

district heating. A ton is the unit used for heat pumps and air conditioners; 1 ton of cooling = 12,000 Btu/h = 3.516 kW.

For the United States, case studies (by type and number of cases) are available from the Geothermal Heat Pump Consortium (http://www.geoexchange.org/index.php?option=com_docman&Itemid=357): residential (7), commercial (5), office building (7), schools (15), affordable housing (5), and government facilities (11).

In the European Union, the growth rate has been huge for GHPs [13], and by the end of 2008 over 785,000 units had been installed, equivalent to 9,000 MWt of capacity [14]. Germany is now the lead market, with 34,450 units installed in 2008 due to new incentives. A database of projects for Europe is available (http://www.sepemo.eu/index.php?id=1). The use of GHPs increased in China in 2007, now estimated at over 200 MWt. The Olympic Village buildings used GHP, which used sewage water as the source.

11.6 ELECTRICITY

Electricity is generated in conventional power plants using the high- and medium-enthalpy heat reservoirs. The advantages of geothermal energy are as follows: It can provide peaking and base load power, and it is modular in that more wells could be drilled if the reservoir is large enough. Some disadvantages are the high mineral content, which causes corrosion problems and environmental problems if downstream water is disposed on the surface; limited distribution of reservoirs (however, not a large problem if EGSs are considered); overproduction with need for pumps or reinjection of fluid; and a long period between start of project and commercial operation.

One aspect that was not given much consideration for EGSs was induction of earthquakes. A project in Basel, Switzerland, was suspended because more than 10,000 seismic events measuring up to 3.4 on the Richter Scale occurred over the first 6 days of water injection [15]. To stimulate the reservoir for a proposed hot, dry rock geothermal project, approximately 11,500 m^3 of water were injected at high pressures into a 5-km deep well from December 2 to December 8, 2006. A six-sensor borehole array, installed at depths between 300 and 2,700 m around the well, recorded more than 10,500 events during the injection phase.

World installed capacity of electric power from geothermal energy is around 11,400 MWe, and production is around 75 TWh/yr (Figure 11.14). The United States [16,17] has the largest capacity (Table 11.3) (3,152 MWe in 2009 and another 124 MWe under construction); however, the geothermal component is only 0.3% of U.S. electric production. Other countries (Figure 11.15) obtain a larger percentage of their electricity from geothermal sources; for example, New Zealand obtains 10%, Iceland 17%, and the Philippines 23%.

The types of geothermal systems for producing electricity are dry rock (steam), flash, and binary with 28%, 64%, and 8%, respectively, of the world geothermal electric power plants (around 500). Average plant size was 44 MW for dry steam; 31 MW for flash; and 3.2 MW for binary. Theoretical thermodynamic efficiency for

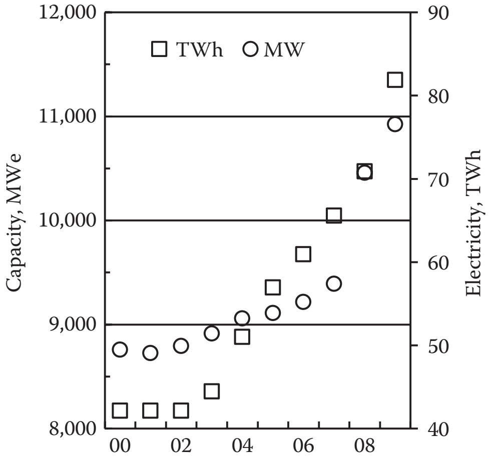


FIGURE 11.14 World installed capacity for electric power and energy from geothermal sources.

TABLE 11.3
Electric Capacity (MW) of Geothermal Power Plants, 2009 Estimate

United States	3,152	Nicaragua	143
Philippines	1,991	Turkey	83
Indonesia	1,192	Papua New Guinea	56
Mexico	1,178	Guatemala	53
Italy	910	Portugal	35
New Zealand	632	China	28
Iceland	580	France	17
Japan	535	Germany	8
El Salvador	204	Ethiopia	7
Costa Rica	197	Australia	1
Russia	185	Austria	1
Kenya	164	Thailand	0.3

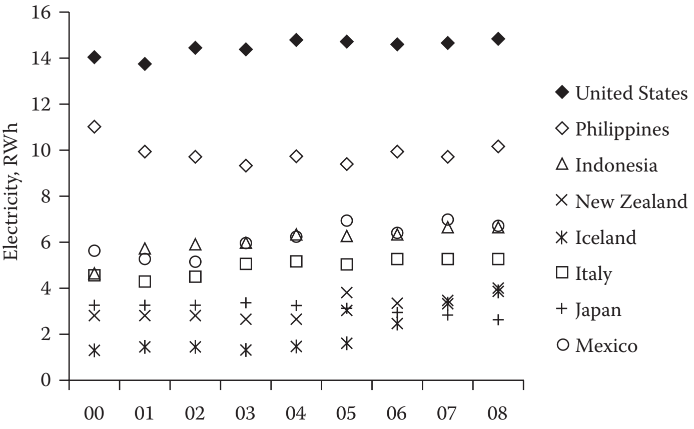


FIGURE 11.15 Leading countries, production of electric energy from geothermal sources.

generation of electricity from conventional steam plants is determined by temperatures (Equation 2.5). A more efficient system would be combined heat and power (CHP), with the lower-temperature heat used before the fluid is reinjected into the reservoir. An EGS 1.5-MWe pilot project is located in Soultz, Alsace, France [18].

11.6.1 Dry Steam

Power plants using dry steam systems (Figure 11.16) were the first type of geothermal power generation plants built. They use steam from the geothermal reservoir as it comes from wells and route it directly through turbine/generator units to produce electricity. An example of dry steam generation can be found in the Geysers region (http://www.geysers.com) in northern California; this is the largest geothermal project in the

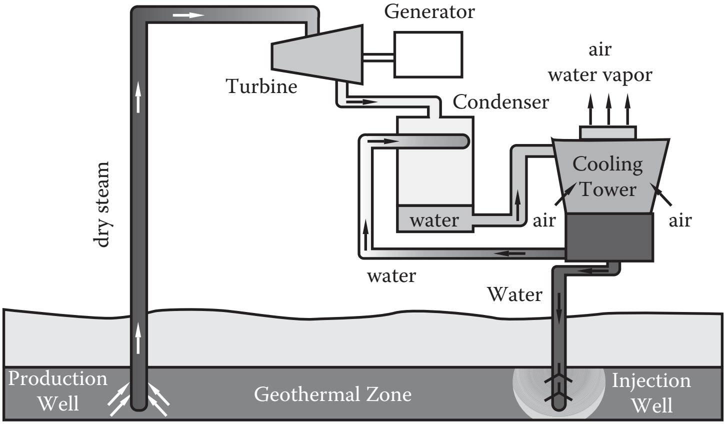


FIGURE 11.16 Diagram of dry steam geothermal system.

world. The area was known for its hot springs in the mid-1800s, and the first well for power production was drilled in 1924. Staring in the 1950s, deeper wells were drilled, and 26 power plants had been built by 1990, with a capacity of more than 2,000 MW.

Because of the rapid development in the 1980s and because of the operation of surface discharge, the steam resource started declining in 1988. Today, the operating capacity is 725 MW; however, the Geysers facilities still meet over 50% of the average electrical demand for northern California. The plants use an evaporative water-cooling process to create a vacuum that pulls the steam through the turbine, producing power more efficiently. However, this process loses 60–80% of the steam to the air, with no reinjection. Although the steam pressure was declining, the reservoir is still hot. To remedy the situation, the Santa Rosa Geysers Recharge Project involves transporting 42,000 m^3 per day of treated wastewater from neighboring communities through a 64-km pipeline and injecting it into the ground to provide more steam. The project came online in 2003, and further expansion is planned to increase the wastewater to nearly 76,000 m^3 per day [19]. One concern with open systems like the Geysers is that they emit some air pollutants. Hydrogen sulfide—a toxic gas with a highly recognizable "rotten egg" odor—along with trace amounts of arsenic and minerals are released in the steam.

11.6.2 FLASH

Flash steam plants (Figure 11.17) are the most common type of geothermal power generation plants in operation today. They use water at temperatures greater than 182°C that is pumped under high pressure to the generation equipment at the surface. On reaching the generation equipment, the pressure is suddenly reduced, and some of the hot water is converted (flashed) into steam, which is used to power the turbine/generator units. The remaining hot water not flashed into steam and the water condensed from the steam are generally pumped back into the reservoir. An example of an area using the flash steam operation is the CalEnergy Navy I flash geothermal power plant at the Coso geothermal field.

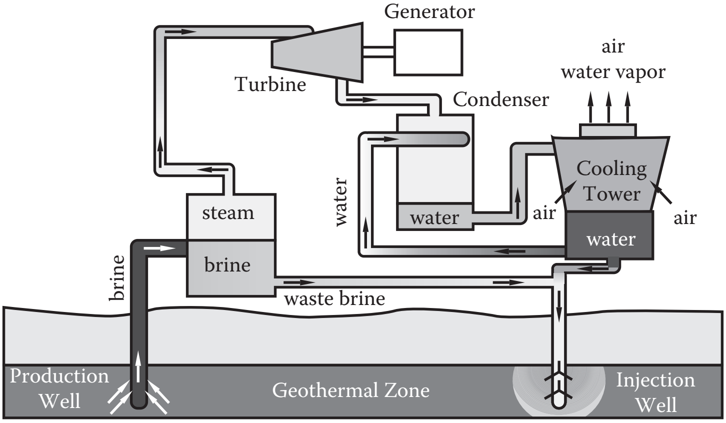


FIGURE 11.17 Diagram of a flash geothermal system.

FIGURE 11.18 Yangbajain, Tibet, geothermal field in 1990.

The most important field in China is the Yangbajain field in Tibet (Figure 11.18), which has eight double flash units for a capacity of 24 MW. There are 18 wells with an average depth of 200 m in the water-dominated shallow reservoir at 140–160°C. The field extension is only 4 km^2, although there are indications of a thermal anomaly of 15 km^2. The annual energy production is approximately 100 GWh, about 30% of the needs of the Tibetan capital, Lhasa. A deep reservoir has been discovered beneath the shallow Yangbajain field, characterized by high temperatures (250–330°C), with an estimated potential of 50–90 MW. A 2,500-m exploratory well was drilled in 2004, reaching the deep reservoir at 1,000–1,300 m. Other plants are installed in Langju, West Tibet (two double flash units, 1 MW each, 80–180°C), and a 1-MW binary power station (60–170°C) is operating in Nagqu. In other regions of China, two small 300-kW plants are operating in Guangdong and Hunan.

The Wairakei, New Zealand, power plant was first commissioned in 1958, and the present output is 140 MWe, with annual production averaging 1,250 GWh at a

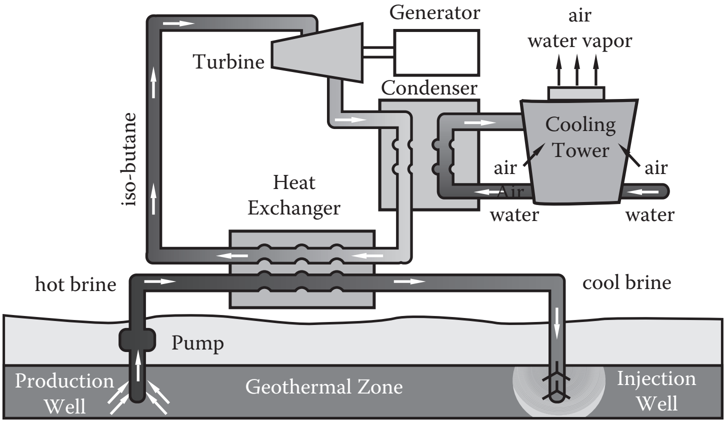


FIGURE 11.19 Diagram of a binary geothermal system.

capacity factor of 93%. At least 150 wells have been drilled in the field, which generally produce fluid at temperatures between 209°C and 261°C. About 5,300 tons of fluid, 1,500 tons steam, and 3,000 tons of water (130°C) per hour are currently taken from the reservoir. Some of the steam is taken directly from shallow dry steam production wells (up to 500 m deep) and piped to the turbines. About half of the separated water is now reinjected, and half is discharged to the Waikato River. All steam condensate is discharged to the river. There had been some subsistence in some areas as the fluids were removed. Information on all geothermal fields in New Zealand is available from the New Zealand Geothermal Association.

11.6.3 Binary Plants

Binary, also known as the ORC, geothermal power generation plants differ from dry steam and flash steam systems because the water or steam from the geothermal source never comes in contact with the turbine/generator units. In the binary system, the water from the geothermal reservoir is used to heat another working fluid, which is vaporized and used to turn the turbine/generator units (Figure 11.19). The advantage of the binary cycle plant is that it can operate with lower-temperature water, 107–182°C using working fluids that have a lower boiling point than water. They also do not produce air emissions. An example of a binary cycle power generation system is the Mammoth Pacific binary geothermal power plants at the Casa Diablo, California, geothermal field.

11.6.4 Combined Heat and Power

A CHP plant fueled by geothermal sources is similar to any other CHP in that the lower-temperature fluid after the production of electricity is used for other purposes (Figure 11.20). For example, separated water from the Wairakei field in New Zealand is used to provide hot fluids for the Netcor tourist facility and provides heat for a prawn farm adjacent to the power station. In Iceland, a system has 45 MWe and

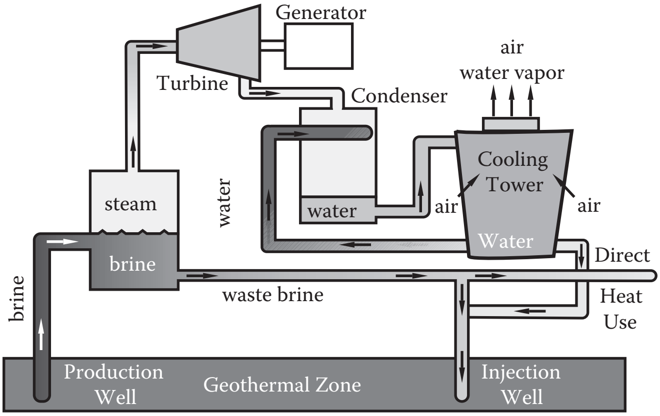


FIGURE 11.20 Diagram of geothermal system for combined heat and power.

150 MWt for district heating for an airport and nine cities. There are two operating CHP plants in Austria and three in Germany. Check with European Geothermal Energy Council for more details (http://www.egec.org).

Landau, Germany: two wells, 3,300 m, 160°C, flow rate 250 m^3/h, 3 MWe
Unterhaching, Germany: two wells, 3,200 m, 122°C, 3.6 MWe
Neustadt-Glewe, Germany: one well, 2,250 m, 122°C, 230 kWe, heat for 1,300 homes

11.7 COMMENTS

Electricity is produced from geothermal sources in 24 countries, with 5 countries obtaining 15–22% of their electric demand. There has been growth in the electric power capacity from geothermal sources since 2007, and by the year 2050 with existing technology, the projection is 70 GW; with EGSs, the projection is 140 GW. Some feel that the usable geothermal resource could be as high as 1,000 GW [17].

The growth rate of GHPs in the developed world is large, and there will be continued growth as China and other countries install GHPs. The projections for 2050 are 750 GWe of GHPs and 50 GWe for direct use (not GHPs). Remember that GHPs still require electricity, but this is more efficient than providing heating and cooling from conventional electric production from fossil fuels, and emissions would be reduced by 45%.

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PROBLEMS

1. OM (order of magnitude): At the present rate of world consumption of energy, how long would geothermal energy last if 5% of world demand for electrical energy came from geothermal resources?
2. List two advantages and two disadvantages of geothermal energy for production of electricity.
3. List two advantages and two disadvantages of geothermal energy for direct use.
4. Go to the project map for the United States at http://geoheat.oit.edu/dusys.htm. Select Nevada. How many power plants are there? Find one with the largest rated power, then give specifications (location, etc.).
5. What is the average capacity factor for geothermal electric power plants for the world for year 2005? Year 2009?
6. How many stripper oil wells are there in the United States?
7. Briefly describe the process of hydraulic fracturing a rock formation.

8. Estimate the number of district heating projects in the United States. How much total energy do they provide per year? Use http://geoheat.oit.edu/dusys.htm to obtain data.
9. Find any district heating system outside the United States. State name, location, and energy provided per year.
10. For Amarillo, Texas, a home is 200 m^2. Estimate the size of ground source heat pump using boreholes. How many boreholes and what depth would be needed?
11. In Indonesia, what percentage of their electricity is from geothermal resources?
12. What percentage of electricity in the United States is generated from geothermal resources?
13. For a binary plant producing electricity, what is the approximate thermodynamic efficiency?
14. If a GHP has a coefficient of performance (COP) of 3.0, estimate how much electrical energy is needed for the heating season for a 200-m^2 house in Amarillo, Texas.
15. If a GHP has an energy efficiency ratio (EER) of 11, estimate how much electrical energy is needed for the cooling season for a 200-m^2 house in Amarillo, Texas.
16. Estimate the geothermal power from the following well: 160°C, 250 m^3/h flow rate, 100°C out temperature.
17. Why is a binary system less efficient than a dry steam system? Give example numbers.
18. What is the main environmental problem associated with the Geysers geothermal plants in California?
19. Check with local installers and get information (type, size) on a GHP for a residence in your area. If possible, check with a homeowner who has a system to obtain their comments. If no systems are in your area, then get a brochure or information on a GHP system for a medium-size home.

12 Water

12.1 INTRODUCTION

Energy from water is one of the oldest sources of energy, as paddle wheels were used to rotate a millstone to grind grain. A large number of watermills, 200 to 500 W, for grinding grain are still in use in remote mountains and hilly regions in the developing world. There are an estimated 500,000 in the Himalayas, with around 200,000 in India [1,2]. Of the 25,000 to 30,000 watermills in Nepal, 2,767 mills were upgraded between 2003 and 2007 [3]. Paddle wheels and buckets powered by moving water were and are still used in some parts of the world for lifting water for irrigation. Water provided mechanical power for the textile and industrial mills of the 1800s as small dams were built, and mill buildings are found along the edges of rivers throughout the United States and Europe. Then, starting in the late 1800s, water stored behind dams was used for the generation of electricity. For example, in Switzerland in the 1920s there were nearly 7,000 small-scale hydropower plants.

The energy in water can be potential energy from a height difference, which is what most people think of in terms of hydro; the most common example is the generation of electricity (hydroelectric) from water stored in dams. However, there is also kinetic energy due to water flow in rivers and ocean currents. Finally, there is energy due to tides, which is due to gravitational attraction of the moon and the sun, and energy from waves, which is due to wind. In the final analysis, water energy is just another transformation from solar energy, except for tides.

The energy or work is force * distance, so potential energy due to gravitation is

$$W = F * d = m * g * H, \text{ J} \tag{12.1}$$

The force due to gravity is mass * acceleration, where the acceleration of gravity $g = 9.8$ m/s^2 and H = height in meters of the water. For estimations, you may use $g = 10$ m/s^2.

For water, generally what is used is the volume, so the mass is obtained from density and volume.

$$\rho = m/V \text{ or } m = \rho * \text{V, where } \rho = 1{,}000 \text{ kg/m}^3 \text{ for water}$$

Then, for water Equation 12.1 becomes

$$PE = \rho * g * H * V = 10{,}000 * H * V \tag{12.2}$$

Example 12.1

Find the potential energy for 2,000 m^3 of water at a height of 20 m.

$$PE = 10{,}000 * 20 * 2{,}000 = 4 * 10^9 \text{ J} = 4 \text{ GJ}$$

If a mass of water is converted to kinetic energy after falling from a height *H*, then the velocity can be calculated.

$$KE = PE$$

or

$$0.5\, m * v^2 = m * g * H$$

Then, the velocity of the water is

$$v = (2 * g * H)^{0.5}, \text{ m/s} \tag{12.3}$$

Example 12.2

For data in Example 12.1, find the velocity of that water after falling through 20 m.

$$v = (2 * 10 * 20)^{0.5} = 20 \text{ m/s}$$

Instead of water at some height, there is a flow of water in a river or an ocean current, such as the Gulf Stream. The analysis for energy and power for moving water is similar to wind energy, except there is a large difference in density between water and air. Therefore, for the same amount of power, capture areas for water flow will be a lot smaller.

$$P/A = 0.5 * \rho * v^3, \text{ W/m}^2 \tag{12.4}$$

Example 12.3

Find the power/area for an ocean current that is moving at 1.5 m/s.

$$P/A = 0.5 * (1.5)^3 = 1.7 \text{ kW/m}^2$$

Power is energy/time, and hydraulic power from water or for pumping water from some depth is generally defined in terms of water flow *Q* and the height. Of course, if you know the time and have either power or energy, then the energy or power can be calculated.

$$P = 10{,}000 * H * V/t = 10 * Q * H, \text{ kW} \tag{12.5}$$

where Q is the flow rate (m^3/s). In terms of pumping smaller volumes of water for residences, livestock, and villages, Q is generally noted as cubic meters per day, so be sure to note what units are used. There will be friction and other losses, so with efficiency ε the power is

$$P = 10{,}000 * \varepsilon * Q * H \tag{12.6}$$

Efficiencies from input to output (generally electric) range from 0.5 to 0.85. Small water turbines have efficiencies up to 80%, so when other losses are included (friction and generator), the overall efficiency is approximately 50%. Maximum efficiency is at the rated design flow and load, which is not always possible as the river flow fluctuates throughout the year or where daily load patterns vary.

The output from the turbine shaft can be used directly as mechanical power, or the turbine can be connected to an electric generator. For many rural industrial applications, shaft power is suitable for grinding grain or oil extraction, sawing wood, small-scale mining equipment, and so on.

12.2 WORLD RESOURCE

Around one-quarter of the solar energy incident on the Earth goes to the evaporation of water; however, as this water vapor condenses, most of the energy goes into the atmosphere as heat. Only 0.06% is rain and snow, and that power and energy of the water flow is the world resource, estimated at around 40,000 TWh/yr. The technical potential (Table 12.1) is 15,000 TWh/yr, and economic and environmental considerations reduce that potential.

TABLE 12.1
Technical Potential, Hydroelectric Production, and Capacity

	Potential, TWh/yr	Production, TWh/yr	Capacity, GW
Asia	5,090		
Asia and Oceanic		798	257
Central and South America	2,790	660	136
Europe	2,710	536	166
Eurasia		245	68
Middle East		22	9
Africa	1,890	97	22
North America	1,670	665	164
Oceania	230		
World	14,380	3,000	822

Source: Production and capacity data for 2007 or 2008 from U.S. Energy Information Administration.

The classification of hydropower differs by country, authors, and even over time. One classification is large (>30 MW), small (100 to 30 MW), and micro (≤100 kW). Some examples are as follows: In China, small hydro refers to capacities up to 25 MW, in India up to 15 MW, and in Sweden up to 1.5 MW. Now, in Europe, small hydro means a capacity of up to 10 MW. Today in China, the classifications are large (>30 MW), small (5 to 30 MW), mini (100 kW to 5 MW), micro (5 to 100 kW), and pico (<5 kW). Others classify microhydro as 10 to 100 kW, so be sure to note the range when data are given for capacity and energy for hydropower.

12.3 HYDROELECTRIC

12.3.1 Large (≥30 MW)

In terms of renewable energy, large-scale hydropower (Figure 12.1) is a major contributor to electric generation in the world, over 3,000 TWh/yr. The world installed capacity for large-scale hydroelectricity has increased around 2% per year, from 462 GW in 1980 to around 850 GW in 2009. However, the hydroelectric percentage of electric power has decreased from 21.5% in 1980 to 16% in 2008 as other sources of electrical energy have increased faster. China is now the leader in installed capacity and generation of electricity (Figure 12.2), with about 14% of their electricity from hydroelectric sources. However, coal in China is the major energy source for the production of electricity, and more coal power has been added than hydroelectric power. In Norway, 98% of the electrical energy is from hydro; Paraguay sells most of its share of electricity from the Itaipu Dam to Argentina. In the United States, the hydroelectric contribution is around 6%. The contribution from small or microhydro plants is difficult to estimate but could represent another 5–10% in terms of world capacity. The capacity factor for hydroelectric power in the world has been fairly consistent at 40–44% from 1980 to 2008. The capacity factor for hydroelectric power in the United States was 37% in 2008.

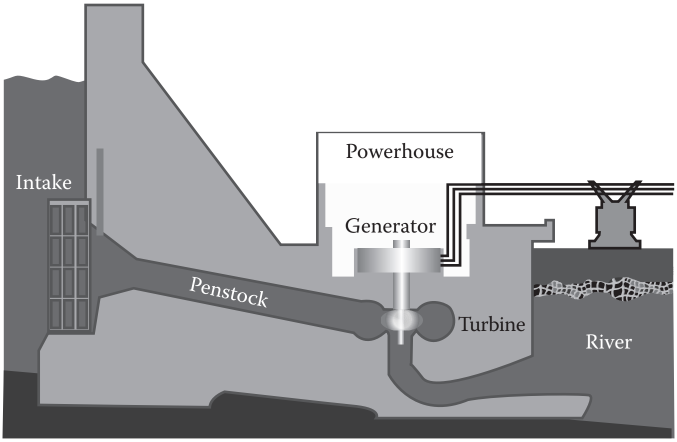


FIGURE 12.1 Diagram of hydroelectric plant. Height of water is level at dam to turbine generator. (From Tennessee Valley Authority.)

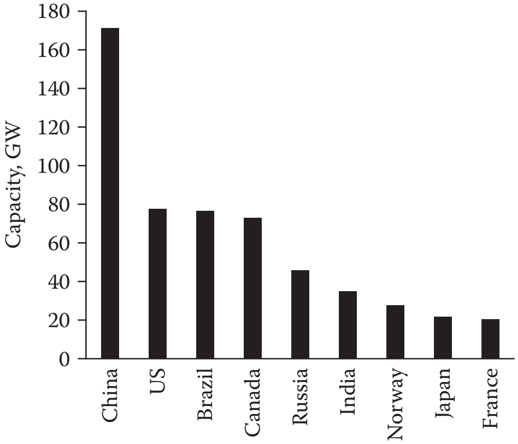


FIGURE 12.2 Installed hydroelectric capacity, 2009, top 10 countries.

TABLE 12.2
Large Hydroelectric Plants in the World, Date Completed, and Capacity

Country	Dam	Year	Capacity, MW
China	Three Gorges	2011	22,500
Brazil-Paraguay	Itaipu	1991	14,700
Venezuela	Guri	1986	10,055
Brazil	Tucurni	1984	8,370
United States	Grand Coulee	1941	6,809
Russia	Sayanao-Shushenskaya	1989	6,500
China	Longtan	2009	6,300
Russia	Krasnoyarsk	1972	6,000
Canada	Robert-Bourassa	1981	5,616
Canada	Churchill Falls	1971	5,429
United States	Hoover	1936	2,079

For photos, see Google images.

Large-scale hydroelectric plants have been constructed all across the world (Table 12.2). The Three Gorges Dam (Figure 12.3) on the Yangtze River is the largest power hydro plant in the world with 18.3 GW and will have a power of 22.5 GW when the rest of the generators are installed in 2011. Previously, the largest project was the Itaipu Dam on the Paraná River between Paraguay and Brazil. The series of dams is 7,744 m long and was built from 1975 to 1991. The Aswan High Dam, Egypt (2,100 MW), was completed in 1967 and produces more than 10 TWh/yr, provides irrigation water for 3.2 million ha, and produces 20,000 tons of fish per year. The entire Temple of Abu Simel had to be moved to higher ground, a major feat in archeology. One of the problems of the Aswan Dam was that farming practices on

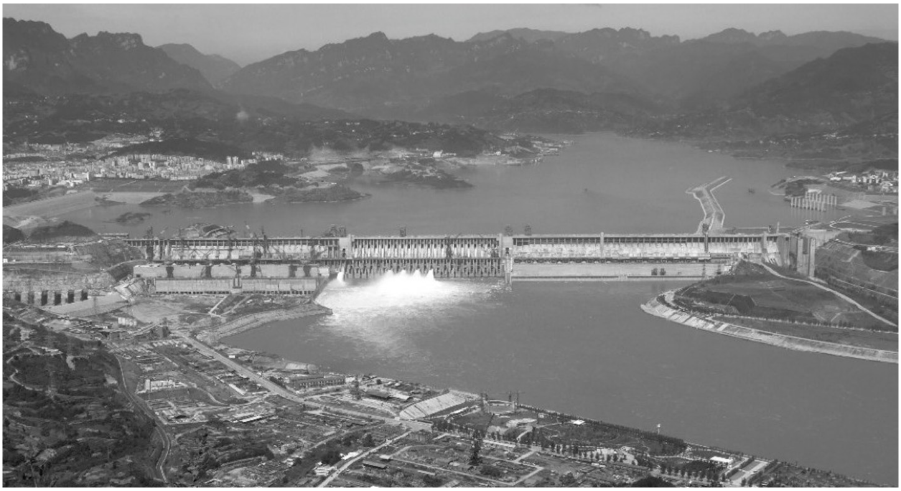


FIGURE 12.3 Three Gorges Dam, 22.5 GW, on the Yangtze River, China. (Courtesy of HydroChina.)

the banks of the river downstream had to be changed since no yearly floods meant no deposition of fertile silt.

The benefits or advantages of hydropower are as follows:

1. Renewable source, power on demand with reservoirs
2. Long life, 100 yr
3. Flood control, water for irrigation and metropolitan areas
4. Low greenhouse gas emission
5. Reservoir for fishing, recreation

Some disadvantages or problems are the following:

1. There is a large initial cost and long construction time.
2. Displacement of population due to reservoir may occur. For example, 1.24 million people were relocated due to the Three Georges Dam.
3. On land downstream, there is loss of nutrients from floods.
4. Drought by season or year may restrict power output due to low water.
5. Lack of passage for fish to spawning areas, for example, salmon.
6. Rivers with high silt content may limit dam life.
7. Dam collapse means many problems downstream. There have been over 200 dam failures in the 20th century, and it is estimated that 250,000 people died in a series of hydroelectric dam failures in China in 1975.
8. Resource allocation between countries can be a problem [4], especially if a series of dams that use a lot of water for irrigation are built upstream of a country.

FIGURE 12.4 Hoover Dam, 2 GW, on the Colorado River, United States. (From U.S. Bureau of Reclamation.)

In the United States, the first commercial hydroelectric plant (12.5 kW) was built in 1882 on the Fox River in Appleton, Wisconsin. Then, commercial power companies began to install a large number of small hydroelectric plants in mountainous regions near metropolitan areas. The creation of the Federal Power Commission in 1920 increased development of hydroelectric power with regulation and monetary support. The government supported projects for hydroelectric power and for flood control, navigation, and irrigation. The Tennessee Valley Authority was created in 1933 [5], and the Bonneville Power Administration was created in 1937 [6]. Construction of the Hoover Dam (Figure 12.4) started in 1931, and when completed in 1936, it was the largest hydroelectric project in the world at 2 GW [7]. Hoover Dam was then surpassed in 1941 by the Grand Coulee Dam (Figure 12.5) (6.8 GW) on the Columbia River [8]. The larger power output is due to the higher volume of water available.

A geographic information system (GIS) application, the Virtual Hydropower Prospector, provides maps and information for the United States [9]. The application allows the user to view the plants in the context of hydrography, power and transportation infrastructure, cities and populated areas, and federal land use. Most of the possible sites will be for small hydro.

In the developed countries with significant hydroelectric capacity, many of the best sites for hydroelectric potential already have dams. Many more reservoirs have been built for irrigation, water supply, and flood control than for hydropower as only 3% of the 78,000 dams in the United States have hydropower. Also, the construction of dams has declined in the United States since 1980 (Figure 12.6). So, there is a

FIGURE 12.5 Grand Coulee Dam, 6.8 GW, on the Colombia River. (From U.S. Bureau of Reclamation.)

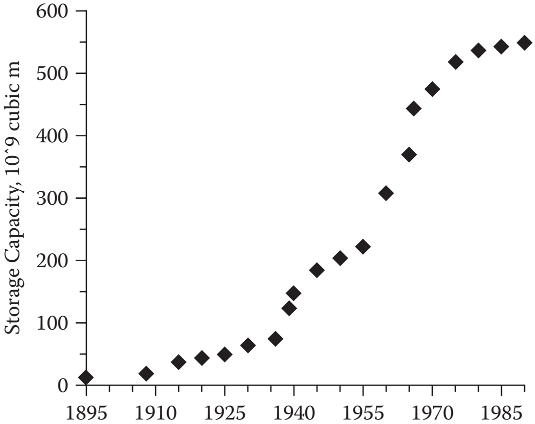


FIGURE 12.6 Reservoir capacity in the United States. (Data from U.S. Geological Survey.)

potential for hydropower by repowering some defunct hydroelectric installations or by new installations of small or medium hydropower at existing dams.

12.3.2 SMALL HYDRO (100 kW TO 30 MW, 10 MW IN EUROPE)

The definition of small hydro differs by country, so the range in Europe is 100 kW to 10 MW and in other countries is up to 25 or 30 MW. The World Energy Council estimated small hydro (up to 10 MW) was around 25,500 MW in 2006, with the major capacity in Europe, nearly 17,000 MW, and the energy production was estimated at

66 TWh. Now, the World Energy Council estimates the installed capacity of small hydro was around 55 GW in 2010, with China having the largest capacity. The current small hydro electricity generation in Europe (European Union-25, the candidate countries, and Switzerland) is around 47 TWh/yr, and the remaining potential is estimated at another 49 TWh/yr. This potential consists mainly of low-head sites (below 30 m).

Hydroelectric plants in the United States are predominantly private (69%); however, 75% of the capacity is owned by federal and nonfederal public owners [10], primarily from large power plants. The percentage of low and small hydropower plants in terms of numbers is 86%. This indicates future expansion for hydroelectric power in the United States will be from distributed generation.

A resource assessment of hydropower for 49 states (no resource in Delaware) identified 5,667 sites (Figure 12.7) with a potential of around 30,000 MW [11]. The criteria were low power (<1 MW) or small hydro (≥1 MW and ≤ 30 MW), and the working flow was restricted to half the stream flow rate at the site or sufficient flow to produce 30 MWa (megawatts average), whichever was less. Penstock lengths were limited by the lengths of penstocks of a majority of existing low-power or small hydroelectric plants in the region. The optimum penstock length and location on the stream was determined for the maximum hydraulic head with the minimum length. The number of sites studied was 500,000, with approximately 130,000 sites meeting the feasibility criteria. Then, application of the development model with the limits on working flow and penstock length resulted in a total hydropower potential of 30,000 MWa. The approximately 5,400 sites that could potentially be developed as small hydro plants have a total hydropower potential of 18,000 MWa. Idaho National Lab also developed a probability factor model, Hydropower Evaluation Software, to standardize the environmental assessment.

12.3.3 MICROHYDRO (≤100 kW)

Estimation of the number of installations and capacity for microhydro is even more difficult. In general, microhydro does not need dams and a reservoir as water is diverted and then conducted in a penstock to a lower elevation and the water turbine. In most cases, the end production is the generation of electricity.

There are thought to be tens of thousands of microhydro plants in China and significant numbers in Nepal, Sri Lanka, Pakistan, Vietnam, and Peru. The estimate for China was about 500 MW at the end of 2008. China started a program, SDDX [12], in 2003 that installed 146 hydro systems with a capacity of 113.8 MW in remote villages in the Western Provinces and Tibet. Hydropower was the predominant system in terms of capacity compared to wind and photovoltaics (PV), with 721 installations (15.5 MW) for villages and 15,458 installations (1.1 MW) for single households. The average size of the hydropower systems was 780 kW, which is much larger than average for the wind and PV systems (22 kW). Case studies are available for a number of countries [13], and software is available from Microhydro [14].

FIGURE 12.7 Present hydropower plants and possible sites for small and low hydropower in the United States. (From Idaho National Laboratory.)

The advantages of microhydro are the following:

1. Efficient energy source. A small amount of flow (0.5 L/min) with a head of 1 m generates electricity with micro hydro. Electricity can be delivered up to 1.5 km.
2. Reliable. Hydro produces a continuous supply of electrical energy in comparison to other small-scale renewable technologies. Also, backup, whether diesel or batteries (which causes operation and maintenance and cost problems), is not needed.
3. No reservoir required. The water passing through the generator is directed back into the stream with relatively little impact on the surrounding ecology.
4. It is a cost-effective energy solution for remote locations
5. Power for developing countries. Besides providing power, developing countries can manufacture and implement the technology.

The disadvantages or problems are as follows:

1. Suitable site characteristics are required, including distance from the power source to the load and stream size (flow rate, output, and head).
2. Energy expansion may not be possible.
3. There is low power in the summer months. In many locations, stream size will fluctuate seasonally.
4. Environmental impact is minimal; however, environmental effects must be considered before construction begins.

Impulse turbines are generally more suitable for microhydro applications compared with reaction turbines because of

Greater tolerance of sand and other particles in the water
Better access to working parts
Lack of pressure seals around the shaft
Ease of fabrication and maintenance
Better part-flow efficiency.

The major disadvantage of impulse turbines is that they are generally unsuitable for low-head sites. Pelton turbines can be used at heads down to about 10 m; however, they are not used at lower heads because their rotational speeds are too slow, and the runner required is too large. The cross-flow turbine is the best machine for construction by a user.

12.4 TURBINES

The two main types of hydro turbines are impulse and reaction. The type selected is based on the head and the flow, or volume of water, at the site (Table 12.3). Other deciding factors include how deep the turbine must be set, efficiency, and cost. Many images are available on the Internet for the different types of turbines.

TABLE 12.3
Classification of Turbine Types

	Head Pressure		
Turbine	**High**	**Medium**	**Low**
Impulse	Pelton Turgo Multijet Pelton	Cross flow Turgo Multijet Pelton	Cross flow
Reaction		Francis	Propeller Kaplan

FIGURE 12.8 Pelton runner (cast) showing bucket shape.

12.4.1 IMPULSE TURBINES

The impulse turbine uses the velocity of the water to move the runner (rotating part) and discharges to atmospheric pressure. The water stream hits each bucket on the runner, and the water flows out the bottom of the turbine housing. An impulse turbine is generally used for high-head, low-flow applications.

A Pelton turbine (Figure 12.8) has one or more free jets of water impinging on the buckets of a runner. The jet is directed at the centerline of the two buckets. Draft tubes are not required for the impulse turbine since the runner must be located above the maximum tail water to permit operation at atmospheric pressure.

A cross-flow turbine (Figure 12.9) resembles a squirrel cage blower and uses an elongated, rectangular-section nozzle to direct a sheet of water to a limited portion of the runner, about midway on one side. The flow of water crosses through the empty center of the turbine and exits just below the center on the opposite side. A guide vane at the entrance to the turbine directs the flow to a limited portion of the runner. The cross flow was developed to accommodate larger water flows and lower heads than the Pelton turbine.

12.4.2 REACTION TURBINES

A reaction turbine develops power from the combined action of pressure and moving water, as the pressure drop across the runner produces power. The runner is in the

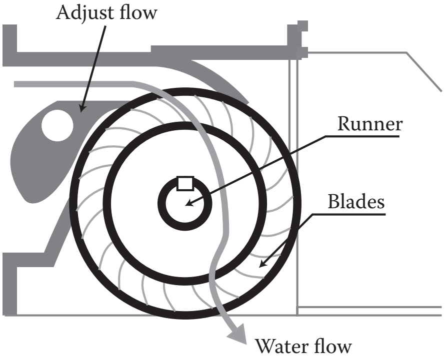


FIGURE 12.9 Diagram of cross-flow turbine.

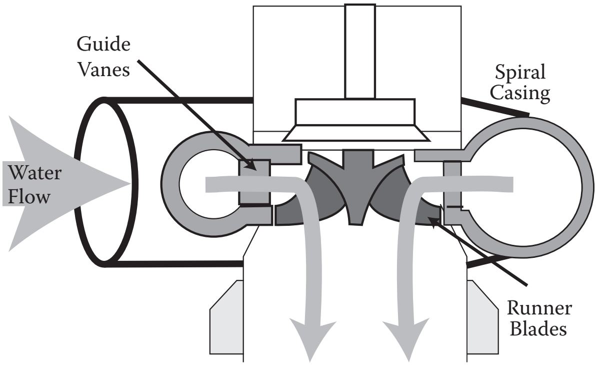


FIGURE 12.10 Diagram of Francis turbine.

water stream flowing over the blades rather than striking each individually. Reaction turbines are generally used for sites with lower head and higher flows.

Francis turbines (Figure 12.10) are the most common for hydropower. They are an inward flow turbine that combines radial and axial components. The runner has fixed vanes, usually nine or more. The inlet is spiral shaped with guide vanes to direct the water tangentially to the runner. The guide vanes (or wicket gate) may be adjustable to allow efficient turbine operation for a range of water flow conditions. The other major components are the scroll case, wicket gates, and draft tube (as water speed is reduced, a larger area for the outflow is needed). However, the Francis turbine can be used for heads to 800 m.

A propeller turbine (Figure 12.11) generally has a runner with three to six blades running in a pipe, where the pressure is constant. The pitch of the blades may be fixed or adjustable. The major components besides the runner are a scroll case, wicket gates, and a draft tube.

There are several different types of propeller turbines:

Bulb: The turbine and generator are a sealed unit placed directly in the water stream.

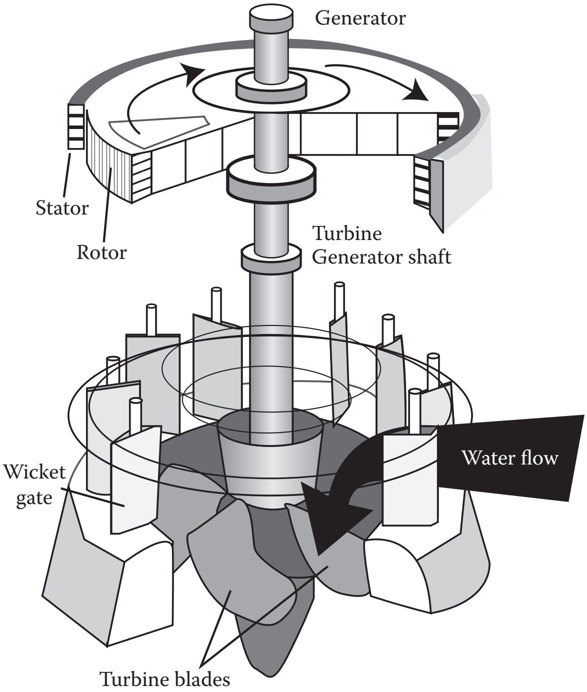


FIGURE 12.11 Diagram of propeller turbine. (From EERE.)

Straflo: The generator is attached directly to the perimeter of the turbine.
Tube: The penstock bends just before or after the runner, allowing a straight-line connection to the generator.
Kaplan: Both the blades and the wicket gates are adjustable, allowing for a wider range of operation.

12.5 WATER FLOW

Kinetic energy turbines, also called free-flow turbines, generate electricity from the kinetic energy of the flowing water, similar to wind turbines, which generate energy from the flowing air. Systems are also referred to as hydrokinetic, tidal in-stream energy conversion (TISEC), or river in-stream energy conversion (RISEC). The systems may operate in rivers, tides, ocean currents, or even channels or conduits for water. Kinetic systems do not require large civil works, and they can be placed near existing structures such as bridges, tailraces, and channels that increase the natural flow of water. For tidal currents, unidirectional turbines are available; rotation is the same, even though current is from opposite directions. One hydrokinetic system has a hydraulic pump to drive an onshore electric generator. Kinetic energy turbines would have less environmental impact than dams, and like wind turbines, they are modular and can be installed in a short time compared to large civil structures.

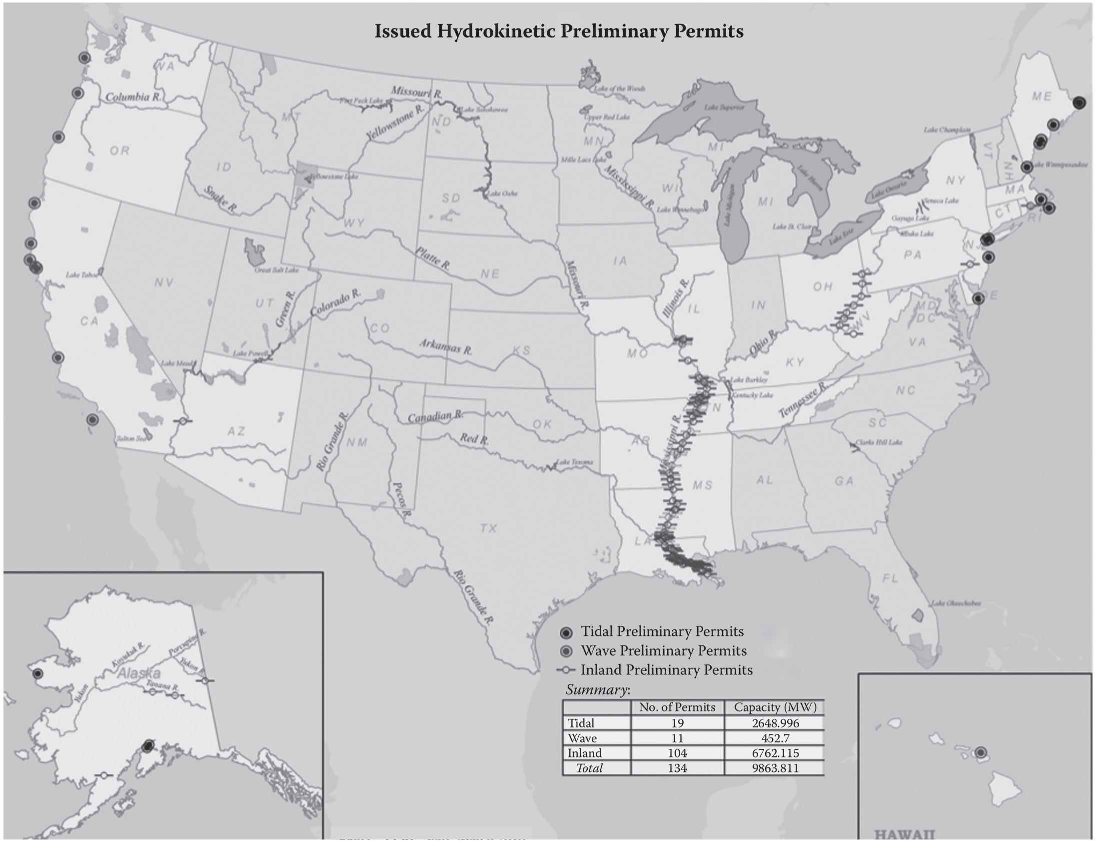
FIGURE 12.12 In-river system, 250 kW, on Mississippi River, Hastings, Minnesota. (Courtesy of Hydro Green.)

The power/area is proportional to the cube of the velocity (Equation 12.4). Large rivers have large flows, and the Amazon, with an average flow of 210,000 m^3/s, has around 20% of the river flow of the world. At the narrows of Óbidos, 600 km from the sea, the Amazon narrows to a single stream that is 1.6 km wide and over 60 m deep and has a speed of 1.8–2.2 m/s. At New Orleans, the speed of the Mississippi is 1.3 m/s, and some sections of the river have flows of 2.2 m/s. At Hastings, Minnesota, a 250-kW hydrokinetic unit located below a dam (4.4 MW hydroelectric) was placed in operation in 2008. The ducted rotor is suspended from a barge with the generator on the barge (Figure 12.12).

The United States could produce 13,000 MW of power from hydrokinetic energy by 2025. As of March 2010, the Federal Energy Regulatory Commission (FERC) had issued 134 preliminary permits for hydrokinetic projects (Figure 12.13) with a total capacity of 9,864 MW. Notice that many of the permits are on the Mississippi River.

The FERC requires consideration of any environmental effects of the proposed construction, installation, operation, and removal of the project. The description should include

1. Any physical disturbance (vessel collision or other project-related risks for fish, marine mammals, seabirds, and other wildlife as applicable)
2. Species-specific habitat creation or displacement
3. Increased vessel traffic
4. Exclusion or disturbance of recreational, commercial, industrial, or other uses of the waterway and changes in navigational safety
5. Any above- or below-water noise disturbance, including estimated decibel levels during project construction, installation, operation, and removal
6. Any electromagnetic field disturbance
7. Any changes in river or tidal flow, wave regime, or coastal or other geomorphic processes



Summary:

	No. of Permits	Capacity (MW)
Tidal	19	2648.996
Wave	11	452.7
Inland	104	6762.115
Total	134	9863.811

FIGURE 12.13 Proposed locations for hydrokinetic projects in the United States, March 2010. (From Federal Energy Regulatory Commission.)

8. Any accidental contamination from device failures, vessel collisions, and storm damage
9. Chemical toxicity of any component of, or biofouling coating on, the project devices or transmission line
10. Any socioeconomic effects on the commercial fishing industry from potential loss of harvest or effect on access routes to fishing grounds

An important factor for water flow is that, at good locations, power will not vary like that of wind turbines, especially for in-river locations, so capacity factors can be much higher. One manufacturer stated that capacity factors should be at least 30% for tides and 50% for in-river systems. As always, the final result for comparison is the cost per kilowatt hour, which should be life-cycle costs.

12.6 TIDES

Tides are due to the gravitational attraction of the moon and the sun at the surface of the Earth. The effect of the moon on the Earth in terms of tides is larger than the effect of the sun, even through the gravitational force of the sun is larger. To find how the gravitational force of the moon distorts any volume of the material body of the Earth, the gradient of the gravitational force of the moon on that volume must be found (a gradient is how force changes with distance; in calculus, it is the differentiation with respect to length). The tidal effects (Figure 12.14) are superimposed on the near-spherical Earth, and there will be two tides per day due to the spin of Earth. When the tidal effects of the sun and moon are aligned, the tides are higher, spring tides. When the continents are added, the ocean bulges reflect from shorelines, which causes currents, resonant motions, and standing waves, so there are some places in the oceans where the tidal variations are nearly zero. In other locations, the coastal topography can intensify water heights with respect to the land. The largest tidal ranges in the world are the Bay of Fundy (11.7 m), Ungava Bay (9.75 m), Bristol Channel (9.6 m), and the Turnagain Arm of Cook Inlet, Alaska (9.2 m). The potential world tidal current energy is on about 2,200 TWh/yr.

Small mills were used on tidal sections of rivers in the Middle Ages for grinding grain. Today, there are only a few tidal systems installed in the world: the French installed a tidal system on the Rance Estuary (constructed from 1961 to 1967) with a power of 240 MW; an 18-MW rim generator at Annapolis Royal, Nova Scotia,

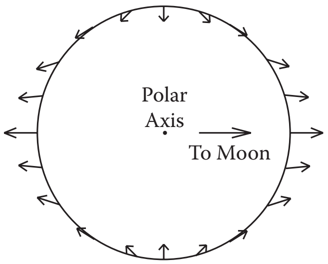


FIGURE 12.14 Tidal forces on the Earth due to the moon.

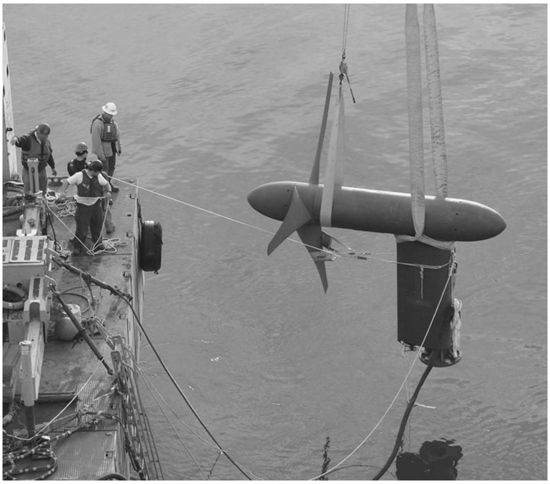


FIGURE 12.15 Tidal turbine, 35 kW, being installed in East River, New York City. (Courtesy of Verdant Power.)

Canada (1984); a 400-kW unit in the Bay of Kislaya, Russia (1968); and a 500-kW unit at Jangxia Creek, East China Sea.

The simplest system for generation of electricity is an ebb system, which involves a dam, known as a barrage, across an estuary. Barrages make use of the potential energy in the difference in height between high and low tides. Sluice gates on the barrage allow the tidal basin to fill on high tides (flood tide) and to generate power on the outgoing tide (ebb tide). Flood generating systems generate power from both tides but are less favored than ebb generating systems. Barrages across the full width of a tidal estuary have high civil infrastructure costs, there is a worldwide shortage of viable sites, and there are more environmental issues.

Tidal lagoons are similar to barrages but can be constructed as self-contained structures, not fully across an estuary, and generally have much lower cost and environmental impact. Furthermore, they can be configured to generate continuously, which is not the case with barrages. Different tidal systems, installed and proposed plants, and prototype and demonstration projects are given in Reference 15.

The potential for tidal in-stream systems was estimated at 692 MW for five states in the United States [16]. A kinetic energy demonstration project (Figure 12.15) is installed in the East River, New York City, and consists of two 35-kW turbines, 5-m diameter, with passive yaw. In 9,000 h of operation, the system generated 70 MWh. Another prototype, SeaGen, is installed in Strangford Narrows, Northern Ireland, with rated power of 1.2 MW at a current velocity of 2.4 m/s and with twin 16-m diameter rotors (Figure 12.16). The rotor blades can be pitched through 180° to generate power on both ebb and flood tides. The twin power units are mounted on winglike extensions on a tubular steel monopole, and the system can be raised above sea level for maintenance. Kinetic energy systems are being considered because of the lower cost, lower ecological impact, increased availability of sites compared to barrages, and shorter time for installation.

FIGURE 12.16 Tidal system, 1.2 MW, in Strangford Narrows, Northern Ireland. (Courtesy of Sea Generation).

Advantages for tidal systems are as follows:

1. Renewable
2. Predictable

Disadvantages or problems are as follows:

1. A barrage across an estuary is expensive and affects a wide area.
2. The environment is changed upstream and downstream for some distance. Many birds rely on the tide uncovering the mudflats so that they can feed. Fish ladders are needed.
3. There is intermittent power as power is available for around 10 h each day when the tide is moving in or out.
4. There are few suitable sites for tidal barrages.

12.7 OCEAN

As with other renewable resources, the ocean energy is large [17]. The global technical resource exploitable with today's technology is estimated to be 20,000 TWh/yr for ocean currents, 45,000 TWh/yr for wave energy, 33,000 TWh/yr for ocean thermal energy conversion (OTEC), and 20,000 TWh/yr for salinity gradient energy. Of course, economics and other factors will greatly reduce the potential production, and future actual energy production will be even smaller.

Besides the environmental considerations mentioned, there are a number of technical challenges for ocean energy to be utilized at a commercial scale:

Avoidance of cavitations (bubble formation)
Prevention of marine growth buildup
Reliability (since maintenance costs may be high)
Corrosion resistance

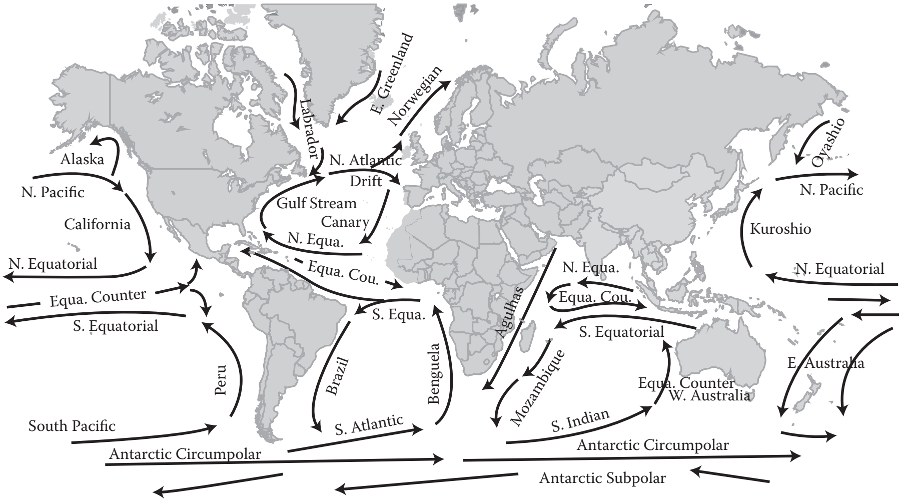


FIGURE 12.17 Major ocean currents in the world. (With permission of Michael Pidwirney.)

12.7.1 CURRENTS

There are large currents in the ocean (Figure 12.17), and detailed information on surface currents by ocean is available [18, only Atlantic and Polar at this time]. For example, the Gulf Stream transports a significant amount of warm water toward the North Atlantic and the coast of Europe. The core of the Gulf Stream current is about 90 km wide and has peak velocities greater than 2 m/s. The relatively constant extractable energy density near the surface of the Gulf Stream, the Florida Straits Current, is about 1 kW/m^2. Although the volume and velocity are adequate for in-stream hydrokinetic systems, an ocean current would need to be close to the shore.

The total world power in ocean currents has been estimated to be about 5,000 GW, with power densities of up to 15 kW/m^2 [19]. The European Union, Japan, and China are interested in and pursuing the application of ocean current energy systems.

12.7.2 WAVES

Waves are created by the progressive transfer of energy from the wind as it blows over the surface of the water. Once created, waves can travel large distances without much reduction in energy. The energy in a wave is proportional to the height squared. In data for wave heights, be sure to note that height is for crest to trough, and amplitude is midpoint to crest.

$$E = 0.5 * \rho * g * H^2/16, \text{ J} \tag{12.7}$$

where H is wave height. This is for a single wave, but in the ocean, there is superposition of waves, and the energy transported is by group velocity. The speed of the wave, wave length, and frequency (or period, which is 1/frequency) are related by

$$\text{Speed} = \text{Wavelength } (\lambda) * \text{Frequency } (f)$$

In deep water where the water depth is larger than half the wavelength, the power per length (meter) of the wave front is given by

$$P/L = \rho * g^2 * H^2 * T/(64 * \pi) \sim 0.5 * A^2 * T, \text{ kW/m} \qquad (12.8)$$

where T is the period of the wave (time it takes for successive crests to pass one point). In major storms, the largest waves offshore are about 15 m high and have a period of about 15 s, so the power is large, around 1.7 mW/m.

Example 12.4

Calculate power/length for waves off New Zealand if the average wave height is 7 m with a wave period of 8 s. The power/length is

$$P/L = 0.5 * 7^2 * 8 = 196 \text{ kW/m}$$

An effective wave energy system should capture as much energy as possible of the wave energy. As a result, the waves will be of lower height in the region behind the system. Offshore sites with water 25–40 m deep have more energy because waves have less energy as the depth of the ocean decreases toward the coast. Losses become significant as the depth becomes less than half a wavelength, and at 20 m deep, the wave energy is around one-third of that in deep water (depth greater than one-half wavelength). The North Atlantic west of Ireland has wavelengths of around 180 m, and off the West Coast of the United States, the wavelengths can be 300 m.

The potential for wave energy (per meter of wave front) for the world is much larger than ocean currents due to the length of coastline (Figure 12.18). The potential for the United States is 240 GW, with an extractable energy of 2,100 TWh/yr based on average wave power density of 10 kW/m. The technically and economically recoverable resource for the United Kingdom has been estimated to be 50–90 TWh of electricity per year or 15–25% of total U.K. demand in 2010. The western coast of Europe and the Pacific coastlines of South America, Southern Africa, Australia, and New Zealand are also highly energetic. Any area with yearly averages of 15 kW/m has the potential to generate wave energy. Note that this threshold excludes areas such as the Mediterranean Sea and the Great Lakes of Northern America.

The resource or wave climate can be obtained from recorded data, and satellites now provide current worldwide data and are used for prediction of wave heights. For wave energy systems, it is also important to determine the statistical occurrence of the extreme waves that can be expected at the site over the lifetime of the system since the system should be designed to survive peak waves.

Once the general area of the wave farm site has been determined, more analysis is needed to pick the best site within that area, for example, by examining the mean wave direction, variability, and the possibility of local focusing of waves. Another essential task includes the calculation of calm periods that allow sufficient time for maintenance and other operations. However, as noted, large waves have lots of power

FIGURE 12.18 Average wave energy (kW/m) for coastlines around the world; values are for deep-water sites. (Courtesy of Pelamis Wave Energy.)

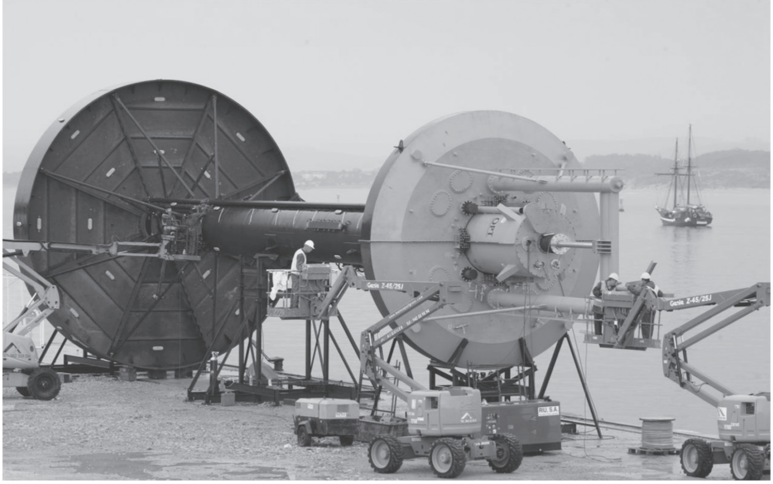
and could damage or destroy the system, so design and construction must take these large waves into account.

The mechanisms for capture of wave energy are point absorber, reservoir, attenuator, oscillating water column, and other mechanisms. There are a number of prototypes and demonstration projects but few commercial projects. A point absorber has a small dimension in relation to the wavelength (Figure 12.19).

The reservoir system is where the waves are forced to higher heights by channels or ramps, and the water is captured in a reservoir (Figure 12.20). Locations for land installations for reservoir and oscillating water column systems will be much more limited than offshore systems; however, land installations are easier to construct and maintain. The Wave Dragon is a floating offshore platform (Figures 12.21 and 12.22).

The Pelamis Wave Energy Converter [20], an attenuator, is a semisubmerged, articulated cylindrical attenuator linked by hinged joints (Figure 12.23). The wave-induced motion of these joints drives hydraulic rams, which pump high-pressure fluid through hydraulic motors via smoothing accumulators. The hydraulic motors drive an electrical generator, and the power from all the joints is fed down a single cable to a junction on the seabed. Several devices (Figure 12.24) can then be linked to shore through a single seabed cable. Current production machines have four power conversion modules: 750-kW rated power, 180 m long, 4-m diameter. The power table and the wave climate are combined to give the electrical power response over time and, from that, its average level and its variability. Depending on the wave resource, the capacity factor is 25–40%.

In an oscillating water column, as a wave enters the column, the air pressure within the column is increased, and as the wave retreats, air pressure is reduced (Figure 12.25). The Wells turbine turns in the same direction irrespective of the airflow direction. The land-installed marine power energy transmitter (LIMPET) unit on Isle of Islay,



(a)

(b)

FIGURE 12.19 PowerBuoy prototype, 40 kW, 14.6 m long, 3.5 m diameter; floats 4.25 m above surface of water. (Courtesy of Ocean Power Technology.)

Scotland [21], has an inclined oscillating water column, with an inlet width of 21 m (Figure 12.26) with the mean water depth at the entrance at 6 m. The system (rated power is 500 kW) has three water columns contained within concrete tubes, 6 m by 6 m, inclined at 40° to the horizontal, giving a total water surface area of 169 m^2. The upper parts of the tubes are connected to a single tube, which contains a Wells generator.

The design of the air chamber is important to maximize the conversion of wave energy to pneumatic power, and the turbines need to be matched to the air chamber. The performance has been optimized for annual average wave intensities of between 15 and 25 kW/m.

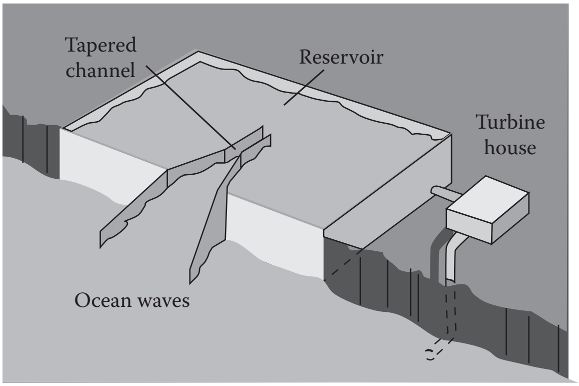


FIGURE 12.20 Diagram of a reservoir system on land.

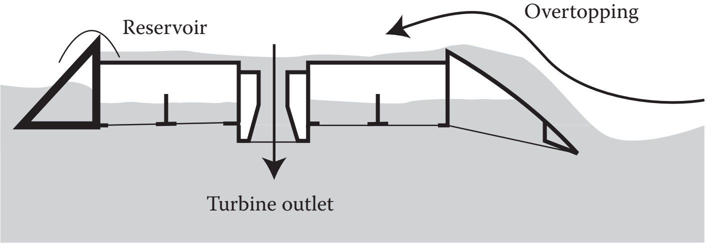


FIGURE 12.21 Diagram of floating reservoir system. (Diagram from Wave Dragon, http://www.wavedragon.net.)

FIGURE 12.22 Prototype floating reservoir system, Nissum Bredning, Denmark. (Courtesy of Wave Dragon, http://www.wavedragon.net.)

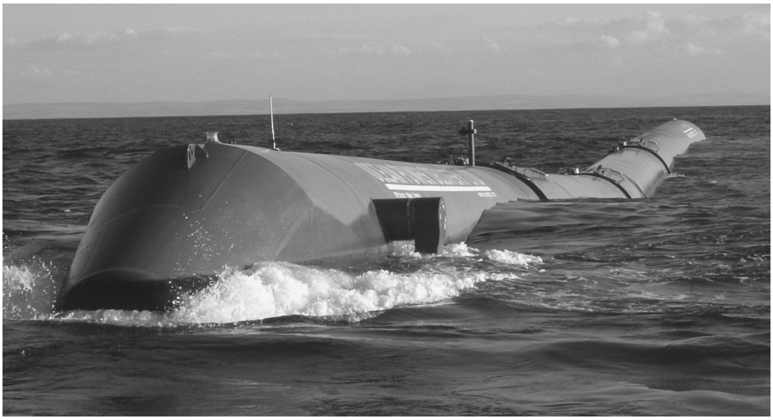


FIGURE 12.23 Sea trial of Pelamis Wave Energy Converter, 750 kW. (Courtesy of Pelamis Wave Energy.)

FIGURE 12.24 Installation of three units at Aguçadoura, Portugal, 2.25 MW total power. (Courtesy of Pelamis Wave Energy.)

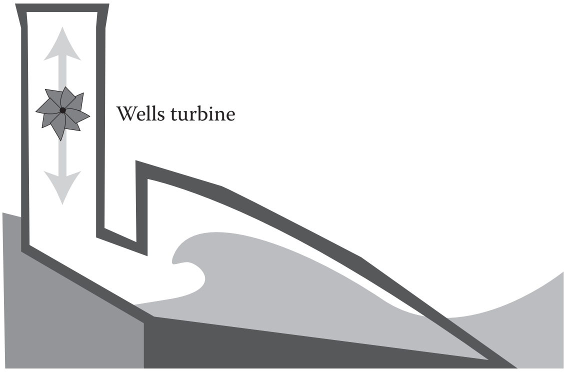


FIGURE 12.25 Diagram of oscillating water column system.

FIGURE 12.26 LIMPET on Islay Island, Scotland, 500 kW; installed 2000. (Courtesy of Voith Hydro Wavgen.).

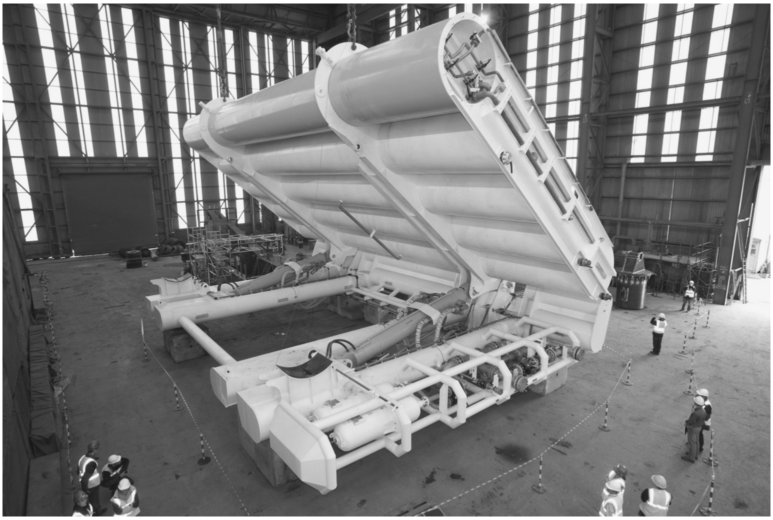


FIGURE 12.27 Oyster hydroelectric wave energy converter, 315 kW; unit installed at Billa Croo, Orkney, Scotland. (Courtesy of Acquamarine Power.)

In another system, waves drive a hinged flap connected (Figure 12.27) to the seabed at around 10 m depth, which then drives hydraulic pistons to deliver high-pressure water via a pipeline to an onshore electrical turbine.

12.7.3 OCEAN THERMAL ENERGY CONVERSION

OTEC for producing electricity is the same as solar ponds, for which the thermal difference between surface water and deep water drives a Rankine cycle. There is

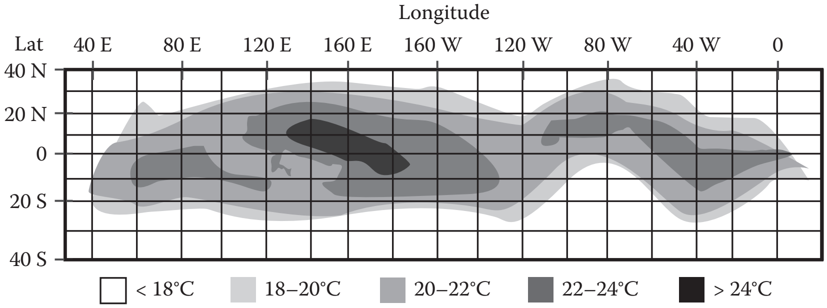


FIGURE 12.28 Ocean thermal differences, surface to depth of 1,000 m. (Source NREL.)

one major difference: The deep ocean water is rich in nutrients, which can be used for mariculture. In both systems, there is the production of freshwater.

An OTEC system needs a temperature difference of 20°C from cold water within 1,000 m of the surface, which occurs across vast areas of the world (Figure 12.28). The systems can be on or near the shore. The three general types of OTEC processes are closed cycle, open cycle, and hybrid cycle.

In the closed-cycle system, heat transferred from the warm surface seawater causes a working fluid to turn to vapor, and the expanding vapor drives a turbine attached to an electric generator. Cold seawater passing through a condenser containing the vaporized working fluid turns the vapor back into a liquid, which is then recycled through the system.

An open-cycle system uses the warm surface water itself as the working fluid. The water vaporizes in a near vacuum at surface water temperatures. The expanding vapor drives a low-pressure turbine attached to an electrical generator. The vapor, which is almost pure freshwater, is condensed into a liquid by exposure to cold temperatures from deep ocean water. If the condenser keeps the vapor from direct contact with seawater, the water can be used for drinking water, irrigation, or aquaculture. A direct contact condenser produces more electricity, but the vapor is mixed with cold seawater, and the mixture is discharged to the ocean. Hybrid systems use parts of both open- and closed-cycle systems to optimize production of electricity and freshwater.

The first prototype OTEC project (22 kW) was installed at Matanzas Bay, Cuba, in 1930 [22]. Then, in the latter part of the 20th century, experimental systems were installed in Hawaii and Japan. An experimental, open-cycle, onshore system was operated intermittently between 1992 and 1998 at the Keahole Point Facility, National Energy Laboratory, Hawaii. Surface water is 26°C, and the deep-water temperature is 6°C (depth of 823 m); the system produced a maximum power of 250 kW. However, the power requirements for pumping the surface (36.3 m^3/min) and deep (24.6 m^3/min) seawater were around 200 kW. A small fraction (10%) of the steam produced was diverted to a surface condenser for the production of freshwater, about 22 L/min. In 1981, Japan demonstrated a shore-based, 100-kWe closed-cycle plant in the Republic of Nauru in the Pacific Ocean. The cold-water pipe was laid on the seabed at a depth of 580 m. The plant produced 31.5 kWe of net power during continuous operating tests.

12.7.4 SALINITY GRADIENT

Salinity gradient energy is derived from the difference in the salt concentration between seawater and river water. Two practical methods for this are reverse electrodialysis and pressure-retarded osmosis; both rely on osmosis with ion-specific membranes. A small prototype (4 kW) started operation in 2009 in Tofte, Norway. The pressure generated is equal to a water column of 120 m, which is used to drive a turbine to generate electricity.

12.8 OTHER

Another application for water flow is ram pumps, where the pressure from water over a drop of a few meters is used to lift a small percentage of that water through a much greater height for water for people or irrigation. Ram pumps were developed over 200 yr ago and can be made locally [23–25]. The operation of a ram pump (Figure 12.29) is as follows:

1. Water from a stream flows down the drive pipe and out of the waste valve.
2. As the flow of water accelerates, the waste valve is forced shut, causing a pressure surge (or water hammer) as the moving water is brought to a halt.
3. The pressure surge causes the check valve to open, allowing high-pressure water to enter the air chamber and delivery pipe. The pressurized air in the air chamber helps to smooth out the pressure surges to give a continuous flow through the delivery pipe.
4. As the pressure surge subsides, the pressurized air in the air chamber causes the check valve to close. The sudden closure of the check valve reduces the pressure in the drive pipe so that the waste valve opens, and the pump is returned to start the cycle again. Most ram pumps operate at 30–100 cycles a minute.

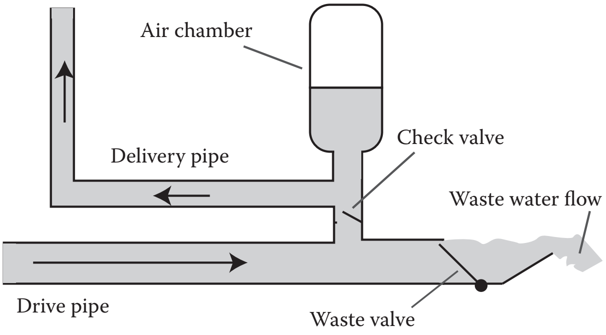


FIGURE 12.29 Diagram of ram pump.

The Alternative Indigenous Development Foundation in the Philippines developed durable ram pumps, and the maintenance is done locally on the moving parts that need regular replacement. The five different size ram pumps can deliver between 1,500 and 72,000 L/day up to a height of 200 m. The 98 ram pumps installed by 2007 were delivering over 900 m^3/day of water, serving over 15,000 people and irrigating large areas of land.

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19. Technology white paper on ocean current energy potential on U.S. continental shelf. http://ocsenergy.anl.gov/documents/docs/OCS_EIS_WhitePaper_Current.pdf.
20. Pelamis Wave Power. http://www.pelamiswave.com/index.php. Gallery and videos are available.

21. Islay LIMPET project monitoring final report. ETSU V/06/00180/00/Rep, 2002. http://www.wavegen.co.uk/pdf/art.1707.pdf.
22. National Renewable Energy Laboratory. Ocean thermal energy conversion. http://www.nrel.gov/otec/.
23. Clemson University. Home-made hydraulic ram pump. http://www.clemson.edu/irrig/Equip/ram.htm.
24. Case Study, Ashden Awards. http://www.ashdenawards.org/winners/aidfoundation.
25. Local manufacture and installation of hydraulic ram pumps for village water supply. http://www.ashdenawards.org/files/reports/AIDFI_2007_technical_report.pdf.

RECOMMENDED RESOURCES

LINKS

Acaua Marine Power, Ocean Power Technologies. http://www.oceanpowertechnologies.com.
Bonneville Power Administration. 2008. Renewable energy technology roadmap (wind, ocean wave, in-stream tidal and solar). http://www.bpa.gov/corporate/business/innovation/docs/2008/RM-08_Renewables_Updated.pdf.
EPRI tidal in-stream energy conversion (TISEC) project. http://oceanenergy.epri.com/streamenergy.html.
European Ocean Energy Association. http://www.eu-oea.com.
Hydropower Research Foundation. http://www.hydrofoundation.org/index.html.
International Energy Agency, Ocean Energy Systems. http://www.iea-oceans.org.
International Hydropower Association. http://www.hydropower.org.
International Network on Small Hydro Power. http://www.inshp.org/main.asp.
International Small-Hydro Atlas. http://www.small-hydro.com.
Microhydro Power. http://practicalaction.org/energy/micro_hydro_expertise.
Microhydro Power. Links to case studies. http://www.microhydropower.net/index.php.
Micro hydro Solomon Islands. http://www.pelena.com.au/pelton_turbine.htm.
National Hydropower Association. http://www.hydro.org.
Oceanweather, current significant wave height and direction by regions of the world. http://www.oceanweather.com/data.
United States, Water Power Technology Program. http://www1.eere.energy.gov/windandhydro/hydro_technologies.html.
Wavebob. http://www.wavebob.com.
Wave Dragon. http://www.wavedragon.net.

PROBLEMS

1. What is the power/area for the current of the Amazon River at the narrows of Óbidos?
2. Suppose a village needs 15 m^3/day for water; the dynamic head is 15 m. Calculate the hydraulic power.
3. What is the average flow rate of the Columbia River at the Grand Coulee Dam? Calculate the power available for the average water height between reservoir and discharge. How does that compare to generator capacity?
4. What is the capacity factor for the kinetic energy system (tidal) in the East River, New York City?

5. List the top three countries and capacity in the world for large hydroelectricity. Note source and date of information.
6. Find any case history for microhydro. Describe general specifications of the system. Note source and date of information.
7. Go to Reference 15 or another source. What is the world installed capacity for tidal systems? Note source and date of information.
8. List two advantages and two disadvantages for onshore wave generation systems.
9. Calculate wave power/length (annual average) for the northwest coast of the United States.
10. Calculate power/area (annual average) for the Gulf Stream off the southern tip of Florida, United States.
11. How much capture area, using an in-stream hydrokinetic system, would be needed for one 5-MW system in a good resource area? Be sure to note where you are locating your system: (a) tidal; (b) ocean current.
12. For a 50-MW point-absorber wave farm, how much area would be needed? Be sure to note where you are locating your system, the number of units, the rated power of the unit.
13. At rated power for the SeaGen tidal system, what is the power coefficient? Use data in text.
14. For the LIMPET wave system, annual wave power input is 20 kW/m. What is the available input power? What is the rated power? Estimate the capacity factor.
15. What is the maximum theoretical efficiency for the OTEC plant in Hawaii? Remember to use degrees kelvin.
16. Briefly describe how power is obtained for an electric generator in a salt gradient system.

13 Storage

13.1 INTRODUCTION

Energy on demand means stored energy, and the most common storage is water in dams, batteries, and biomass. Of course, fossil fuels are stored solar energy from past geological ages. However, what means are available for storing renewable energy today? Storage is a billion-dollar idea, and anyone who comes up with cheap storage will be richer than Bill Gates. Economic storage would mean no new electric power plants would have to be constructed for many years, as energy could be stored from existing power plants during periods of low demand [1–3].

Energy cannot be created or destroyed, only transformed from one form to another, so in reality there are only two forms for storage: kinetic energy and potential energy. Storage as kinetic energy could be as flywheels, and thermal storage could be as heat (internal kinetic energy). For example, a passive solar home would use concrete or rock and maybe water for 2–4 days of thermal storage, and a ground source heat pump would use the earth as seasonal thermal storage. Compressed air is kind of a mixture; it is mechanical, but there is a thermal change. Super flywheels with high revolutions per minute and composite materials for strength have been designed and are used in uninterrupted power supplies and prototypes on buses. I kind of like flywheels as you would drive your car into the filling station and say "wind it up" rather than "fill it up."

Potential energy is due to the generalized interactions (gravitational, electromagnetic, nuclear weak, and strong), of which we consider gravitational and electromagnetic for storage systems. The gravitational potential energy is primarily water (Chapter 12): dams, tidal basins, and pumped storage. The electromagnetic interaction includes chemical, phase change, magnetic (superconductor magnetic energy storage, SMES), electric (capacitors), and mechanical (springs) interactions. Chemical storage is by batteries, photosynthesis, production of methane and hydrogen, fertilizer, and other types. The storage of gas requires high pressure, converting to liquid, or as a chemical compound, or for example, storing hydrogen in metal hydrides. Of course, lots of solar energy is stored in chemical compounds as food and fiber (solar energy to sugar, starches, cellulose, etc., liquid precursors for biofuels).

Thermal storage could be thermal mass, ice, molten salt (concentrating solar power [CSP] systems), cryogenic (liquid air, nitrogen, hydrogen), earth (heat pump), solar pond, and phase change. Molten salt for thermal storage is being used in combined heat and power systems. The main components for consideration of different storage systems are

Energy density
Efficiency and rate of charge/discharge
Duration or lifetime (number of cycles)
Economics

TABLE 13.1
Relative Rating of Storage Technologies

Type	Advantage	Disadvantage
Pumped hydro	High capacity	Site requirements
Compressed air	High capacity	Site requirements
Flywheels	High power	Low energy density
Superconductor magnetic	High power	Low energy density
Capacitors	Large number of cycles, high efficiency	Low energy density
Batteries		
Flow	High capacity	Low energy density
Metal-air	High energy density	Charging difficult
Pb-acid		Limited life when deep discharged
Li ion, Ni-Cd, Na-S	High power, energy density	
Hydrogen		Low energy density

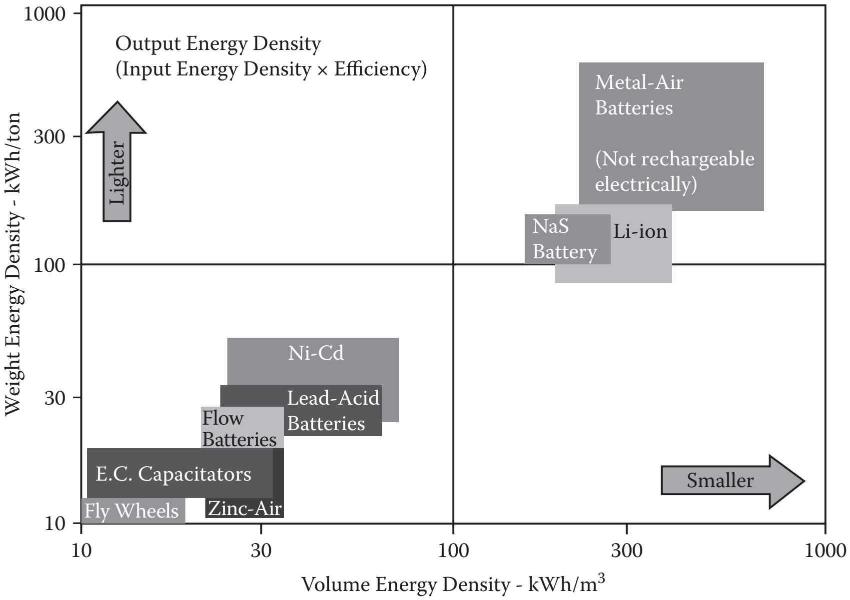

FIGURE 13.1 Energy density by weight and volume for electric storage. (Courtesy of Electricity Storage Association.)

Different storage technologies (Table 13.1) can be for power or energy. Energy density and then size and weight for some applications are important factors (Figure 13.1). Liquid fuels have large energy density, while hydrogen gas has low energy density. In general, storage efficiencies range from 50% to 80%, and the lifetimes vary widely from 100 yr for dams to 5 to 10 yr for lead acid batteries in a photovoltaic (PV) system, to less than an hour for nonrechargeable batteries (Figure 13.2).

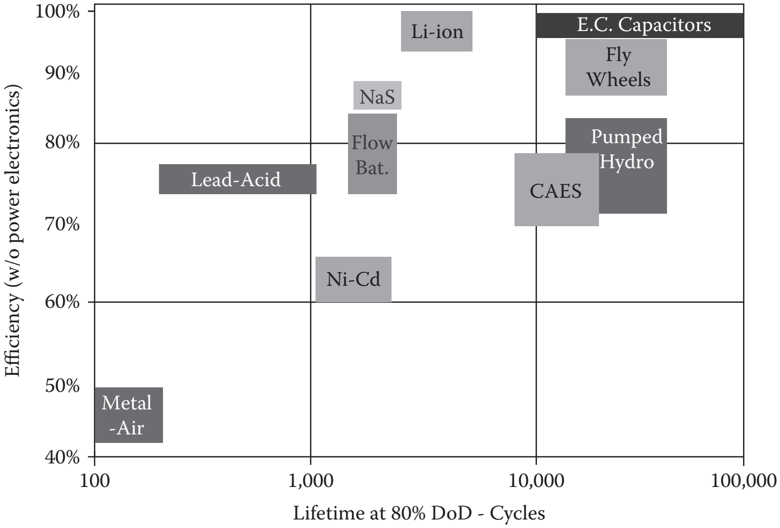

FIGURE 13.2 Efficiency and lifetime for different electric storage systems; CAES efficiency is for the storage only. (Courtesy of Electricity Storage Association.)

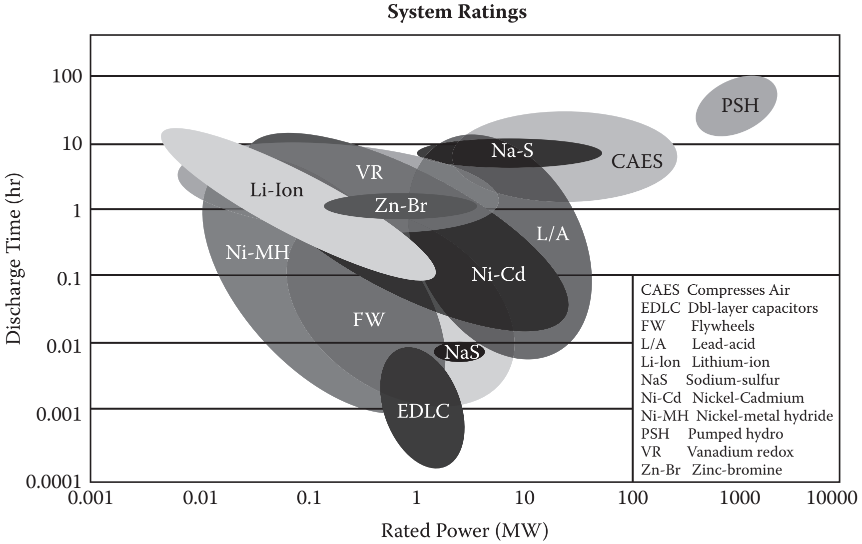

FIGURE 13.3 Discharge time and rated power of installed systems, electric storage. (Courtesy of Electricity Storage Association.)

The maximum rate and best rate of charging and discharging the storage is related to type and use of storage (Figure 13.3). Whether energy storage is included in an application and the type of storage is driven by economics (Figures 13.4 and 13.5) and specific power and energy (Figure 13.6). An electric car that takes 6 h to charge the batteries could not be used on a cross-country trip, even if charging stations were

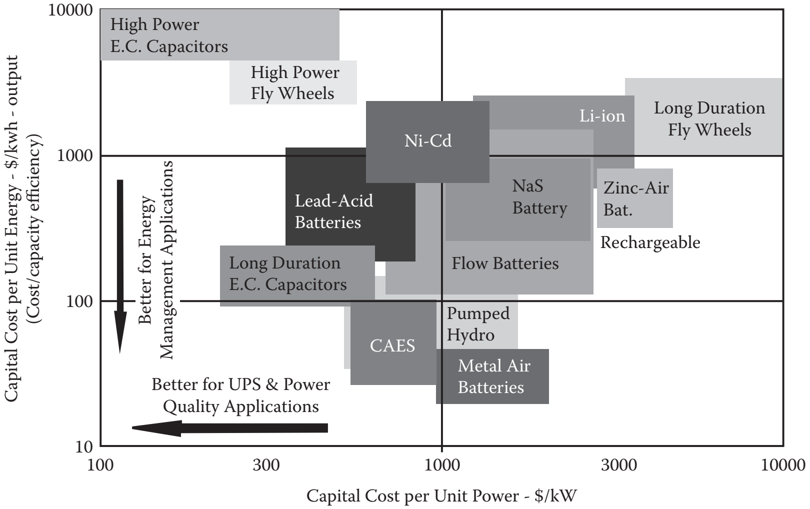

FIGURE 13.4 Capital costs for electric storage systems. (Courtesy of Electricity Storage Association.)

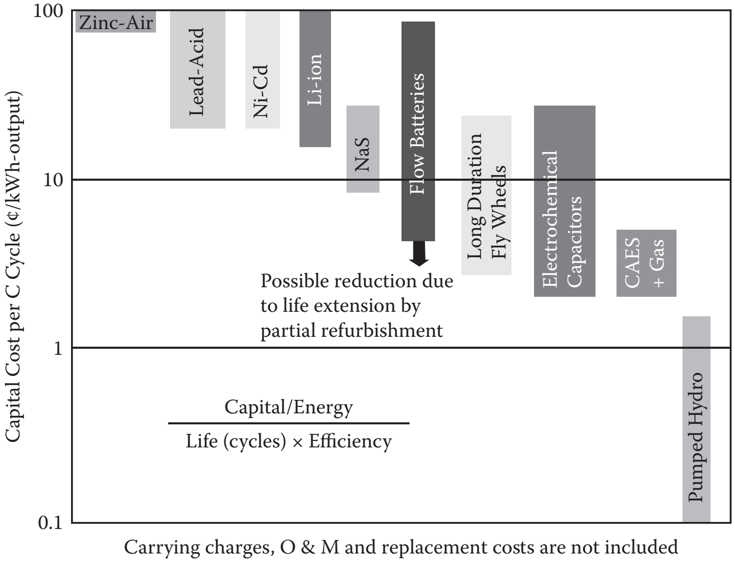

FIGURE 13.5 Cost per cycle for electric storage systems. (Courtesy of Electricity Storage Association.)

available. Thus, you can see how versatile liquid fuels are for transportation. Also, the storage requirements for high power, short time is different from energy storage for a few days. For utilities (Table 13.2), the only large storage systems are pumped storage and compressed air energy systems (CAESs); however, battery systems for power shaving, conditioning, and reducing the variability from renewable energy

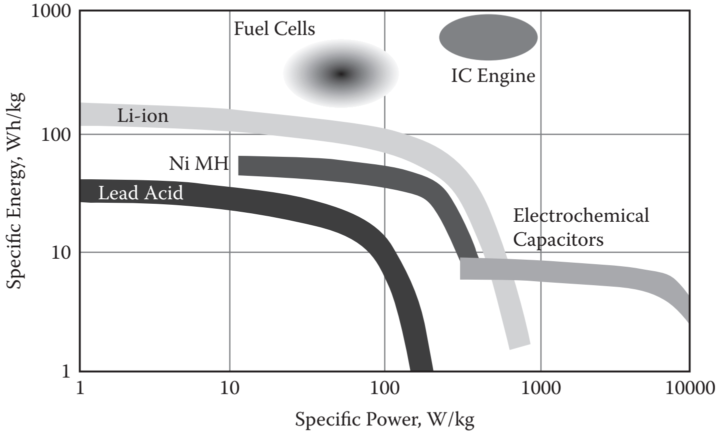

FIGURE 13.6 Energy and power by weight for different batteries.

TABLE 13.2
Electricity Storage Capabilities

	Pumped Hydro	Compressed Air	Batteries
Power	4 GW	50–300 MW	50 kW to 50 MW
Capacity	25,000 MWh	2,500 MWh	50–250 MWh
Duration	12 h	4–24 h	1–8 h
Response	5–15 min	2–12 min	4 ms
Cycle efficiency, %	70–85	70–85	60–90
Life	30–50 yr	30–50 yr	5–10 yr

sources have been installed. Both pumped hydro and compressed systems have long life and a large number of cycles. For remote village power systems and stand-alone systems, batteries are the most common storage.

The electricity produced by a generator cannot be stored; energy in minus energy losses is the demand, so the generation supplies that amount of demand, which varies by time of day and season. In addition, a utility system must meet peak demands and have spinning reserve for unforeseen conditions. If demand exceeds capacity, then users are taken off the grid. In some parts of the world, there are rolling blackouts, or electricity is only available for certain time periods. Finally, extreme events may force shutdown of the total grid. A good source for information on storage for electricity is provided by the Electricity Storage Association (http://www.electricitystorage.org/ESA/home). Check out the Technologies section.

13.2 PUMPED HYDRO

Pumped storage has two reservoirs, and the same motor/generator can be used to pump water to the upper reservoir during periods of low demand and then generate electricity during periods of high demand, just as any other hydroelectric plant with

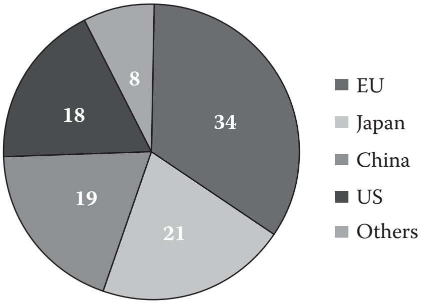

FIGURE 13.7 World pumped hydro storage, percentage.

a reservoir. The pumped hydro levels the load for other generators on the grid. The need for a pump-priming head places the motor/generator below the water level of the lower reservoir. Pumped storage systems generally have a high head to reduce the size of the reservoirs. Pumped storage can respond to full power within minutes, and if operated in the spinning mode, which use less than 1% of their rated power, they can be changed to a pump or generator mode within 10 s. Nuclear power plants can only change load slowly, and other base load plants can be operated at maximum efficiency through the use of pumped storage to absorb their output at night during low demand. There are motor/generator, friction, and evaporation losses, so the overall efficiency of a storage cycle is around 75%.

The advantages are as follows:

Improved energy regulation and operation of the supply grid
Ancillary services such as standby and reserve, black-station start, frequency control, and flexible reactive loading

The disadvantages are as follows:

High capital cost due to fairly large reservoirs
As for other dams, land area needed, collapse could happen

There are over 120 GW of pumped storage in the world (Figure 13.7). In 2009, the United States had 21.9 GW of pumped storage, accounting for 2.5% of base load generating capacity. In 2009, the European Union had 40.9 GW net capacity of pumped storage out of a total of 140 GW of hydropower, and that represented 5% of total net electrical capacity in the European Union. China had 23 GW of pumped storage from units 1 GW and larger. Japan has installed a system that uses seawater for pumped storage.

Case Study

The Taum Sauk plant in the United States is a pure pump-back operation in that there is no natural flow into the upper reservoir. Construction began in 1960, and operation began in 1963. The two pump-turbine units were each

FIGURE 13.8 Upper reservoir for Taum Sauk pumped hydro plant, Missouri. Notice scouring of the creek due to wall failure. (Source: U.S. Geological Survey photo 037.)

175 MW and were upgraded in 1999 to 225 MW. The original upper reservoir had a capacity of 5,366,000 m³ and 244-m head to the hydroelectric plant and was connected by a 2,100-m tunnel through the mountain. The upper reservoir suffered a catastrophic failure [4] on December 14, 2005, due to a software error; water continued to be pumped to the reservoir when the reservoir was full, and then high winds from Hurricane Rita caused a breach in the reservoir walls (Figure 13.8). Approximately 4 million m³ of water were released in less than 0.5 h; luckily, no one was killed. The upper reservoir dam has been replaced with a roller-compacted concrete dam.

13.3 COMPRESSED AIR

Compressed air energy storage (CAES) is a peaking power plant that consumes 40% less natural gas than a conventional gas turbine, which uses about two-thirds of the input fuel to compressed air. In a CAES plant, air is compressed during off-peak periods and then is utilized during peak periods. The compressed air can be stored in underground mines or salt caverns, which take 1.5 to 2 yr to create by dissolving the salt.

For an ideal gas, the amount of energy for an isothermal process from a pressure difference is

$$E = m\,R * T * \ln(P_A/P_B) = P * V * \ln(P_A/P_B),\ \text{J} \qquad (13.1)$$

where P is the absolute pressure, V is the volume, m is the amount of gas, R is the ideal gas constant, and T is the absolute temperature in degrees kelvin. The approximation is 100 * (P_A/P_B) kJ/m^3 for gas at around atmospheric pressure.

A 290-MW CAES was built in Hundorf, Germany, in 1978, and a 110-MW CAES was built in McIntosh, Alabama, in 1991. The CAES in Germany provides 2 h storage from 300,000 m^3 at a pressure of 48,000 Pa (1,000 psi). The CAES in Alabama provides 26 h of storage from a 540,000 m^3 cavern at a pressure of 53,000 Pa (1,100 psi). The construction took 30 months and cost \$65 million (about \$591/kW).

There are two proposed plants in the United States. A 2,700-MW CAES in Norton, Ohio, will compress air to 1,500 psi in an existing limestone mine 607 m underground and is at the developmental stage. Iowa Stored Energy Park includes more than 100 municipal utilities in Iowa, Minnesota, and the Dakotas. The CAES plant would be 268 MW with about 50 h of storage (13,400 MWh), and it will utilize variable wind energy for input. In the plains region, at 40 m and above, there is more wind energy at night than during the day, which is a poor load match to the demand of the grid.

A CAES is relatively low efficiency, with a cost over \$1,000/kW of storage. The input compressed air has to be cooled because the temperature would be too high for a salt cavern. The Electric Power Research Institute (EPRI) estimates that 80% of the United States has geology suitable for a CAES. Compressed air can be used for other applications, to power tools, pump water, and even power vehicles.

13.4 FLYWHEELS

Flywheels store energy due to rotational kinetic energy, which is proportional to the mass and the square of the rotational speed.

$$E = 0.5 * I * \omega^2, \text{ J} \tag{13.2}$$

where I is the moment of inertia (kg m^2), and ω is the angular velocity (radian/s). For a mass M and radius R, the moment of inertia for a ring is $I = M * R^2$, and for a homogeneous disk, $I = 0.5 * M * R^2$

Increasing the revolutions per minute increases the energy density, so high-speed flywheels have revolutions per minute in the tens of thousands. Low-speed flywheels are made from steel, and high-speed flywheels are made from carbon fiber or fiberglass. High-speed flywheels are housed in a low vacuum and use magnetic bearings to reduce or eliminate those frictional losses. Advances in power electronics, magnetic bearings, and materials have resulted in direct current (DC) flywheels. Note that if there is material failure, the container has to retain that energy inside. Cycle efficiency is around 80%.

Because of longer life, simpler maintenance, smaller footprint, and fast reaction time, flywheel systems are used in uninterruptible power supply (UPS) systems [4] to provide backup power for the first 15 s until other backup generators come online. Installed cost depends on type, and range from \$150 to \$400/kW. Another application for flywheels is for cranes for ship and rail yards, where the flywheel provides the short period, high energy for lift, and then energy is returned to the flywheel as objects are lowered.

Flywheels have been used in trains, cars, and buses; however, they were primarily experimental or prototypes. In the past, there were flywheels on tractors to smooth out the rotation of the crankshaft of two-cylinder engines. A hybrid vehicle could use flywheels for acceleration in conjunction with a smaller internal combustion engine, much like hybrid vehicles with batteries. Remember that, in a car, the flywheel is a gyroscope, which will change the handling.

13.5 BATTERIES

Batteries are common all over the world as lead-acid batteries are used for vehicles, and batteries are used for low-power and low-energy applications for lights, radio, TV, and electronic devices. PV or PV with rechargeable batteries has now replaced batteries for very low-power applications. Batteries convert chemical energy into electrical energy using electrodes immersed in a medium (liquids, gels, and even solids) that supports the transport of ions or electrolyte reactions at the two electrodes. Individual cells are placed in series for higher voltage and in parallel for higher current. Since there is an internal resistance and due to other factors, there are losses in charging and discharging a battery.

The power is the product of the voltage and current; however, batteries are generally specified by volts and storage capacity C_B, which is related to stored energy. C_B is the amount of charge that a battery can deliver to a load. It is not an exact number because it depends on the age of the battery (number of cycles), temperature, state of charge, and rate of discharge. If you discharge a lead-acid battery to essentially zero a few times, you have drastically reduced its lifetime. As a first approximation, the energy is

$$E = V * C_B, \text{ J} \tag{13.3}$$

where V is the voltage, and C_B is the battery capacity (Ah).

Example 13.1

A 12-V battery is rated at 100 Ah. It could deliver 5 Ah for 20 h, $E = 12 * 20$ Wh or 1.2 kWh. However, at a faster discharge rate, the values would be lower: 85 Ah for 10 h, 70 Ah for 5 h.

Decreased temperature results in less battery capacity, and for a lead-acid battery, storage capacity decreases around 1% for every 1°C drop in temperature. Remember those cold mornings when the battery just had enough juice to start your car? Explosions by short circuit and generation of hydrogen plus disposal of used batteries and toxic chemicals are problems.

13.5.1 LEAD ACID

Lead-acid batteries are a low-cost and widely used technology for power quality, UPS, and some applications for spinning reserve. However, they are limited for large amounts of energy storage for utilities, primarily due to a short cycle life. As noted, the rate of charge/discharge (Figure 13.9) affects capacity (fast rate, fewer volts), and depth of discharge affects life (Figure 13.10). So, there is a trade-off between cost of more batteries and lifetime. Even with that disadvantage, lead-acid batteries are the most common energy storage for remote village power and stand-alone systems [6, Chap. 11, Energy Storage]. Examples of lead-acid systems are a 10-MW, 4-h

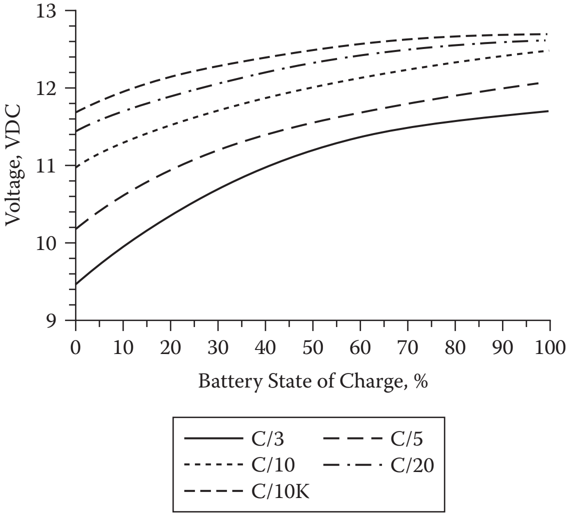

FIGURE 13.9 Battery voltage (12-V battery) and state of charge depend on rate of charge/discharge (C/Number of hours).

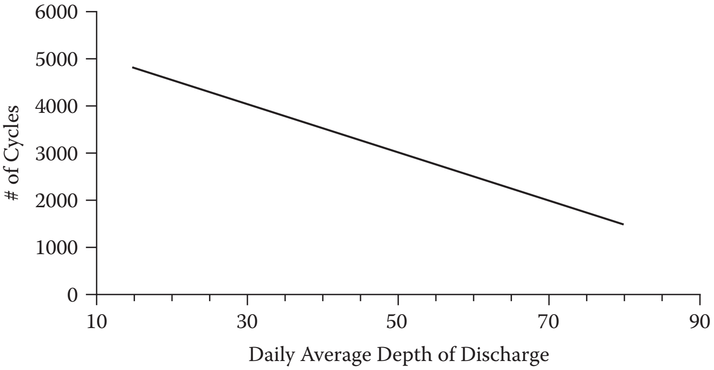

FIGURE 13.10 Life, number of cycles, for lead-acid battery versus depth of discharge.

system in Chino, California; a 20-MW, 40-min system in San Juan, Puerto Rico; and a 3.5-MW, 1-h system in Vernon, California.

Some battery practices for small renewable systems are as follows:

Do not add new batteries to old sets.
Avoid more than two (three at most) parallel strings.
Do not use different types of batteries in the same set.
Keep cable lengths the same.
Keep all components clean and connections tight.
Follow the manufacturer's recommendations for charging and equalization.
Do not wear jewelry when working on batteries.
Use insulated tools.

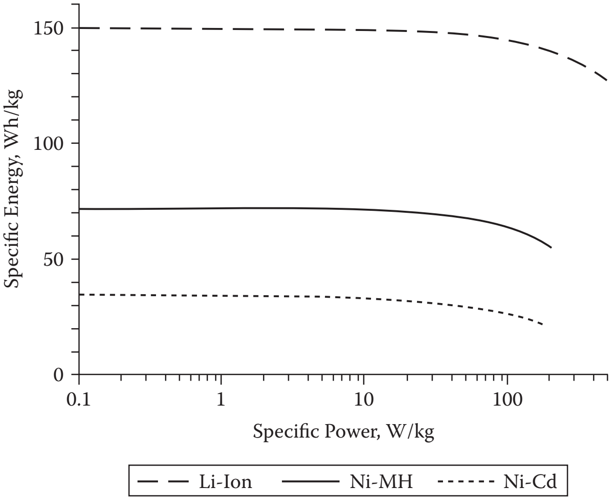

FIGURE 13.11 Energy and power by weight for advanced batteries.

Wear protective clothing and eye protection when working on batteries.
There should be no smoking and no sparks around batteries.
Keep a battery log.

In general, car batteries are not suitable for storage in renewable energy systems, although they are available and have been used for some small systems.

13.5.2 LITHIUM ION

The main advantages of lithium ion batteries (Figure 13.11), compared to other advanced batteries, are as follows:

High energy density (300–400 kWh/m^3, 130 kWh/ton)
High efficiency (near 100%)
Long cycle life (3,000 cycles at 80% depth of discharge [DOD]).

Lithium ion batteries have captured 50% of the small portable market, and hybrid vehicles are one of the main drivers behind their increased use. However, they cost more.

13.5.3 SODIUM SULFUR

The performance of the commercial sodium sulfur battery banks is as follows:

Capacity of 25–250 kW per bank
Efficiency of 87%
Lifetime of 2,500 cycles at 100% DOD or 4,500 cycles at 80% DOD

Cost is around $2,500/kW.

Sodium sulfur batteries of over 270 MW at 6 h of storage have been demonstrated at numerous sites in Japan. The largest installation is a 34-MW, 245-MWh unit for a wind farm in northern Japan. U.S. utilities have deployed around 20 MW for peak shaving, backup power, wind farms, and other applications. Presidio, Texas, frequently experienced power outages due to their long connection to the main grid: a single, 60-year-old transmission line. A 4-MW, 32-MWh sodium sulfur battery was installed, which stores enough electricity for the whole town. Cost of the battery and substation was estimated at $23 million. Xcel Energy installed a 1-MW battery storage next to an 11-MW wind farm [7]. The twenty 50-kW modules store about 8.2 MWh, which could power 500 homes for 7 h.

13.5.4 FLOW BATTERIES

A flow battery converts chemical energy to electricity; electrolytes containing one or more dissolved electroactive species flows through an electrochemical cell. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the reactor, although gravity feed systems are also known. The power and energy ratings are independent of each other. Flow batteries can be rapidly recharged by replacing the electrolyte liquid while simultaneously recovering the spent material for reenergization.

Vanadium can exist in four different oxidation states, so the vanadium redox battery [8] uses this to make a battery that has just one chemical electrolyte instead of two (Figure 13.12). H^+ ions (protons) are exchanged between the two electrolyte tanks through the permeable polymer membrane. The net efficiency of this battery can be as high as 85%. Current installations include

1.5-MW UPS system in a semiconductor fabrication plant in Japan
275-kW output balancer, Tomari Wind Hills, Hokkaido, Japan

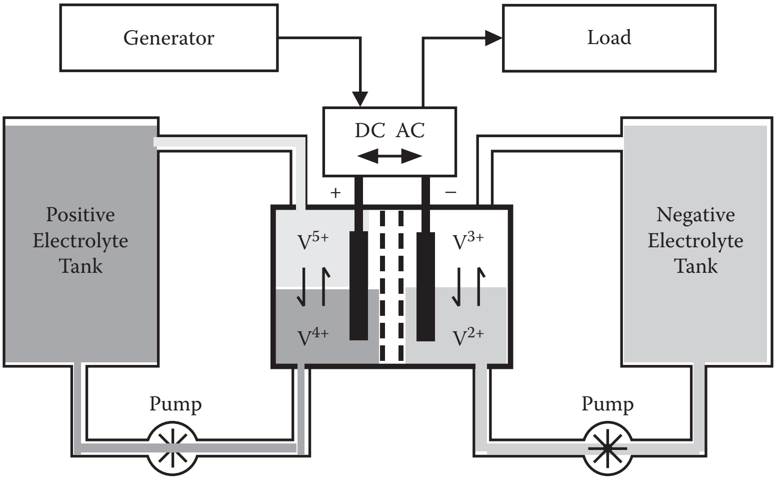

FIGURE 13.12 Diagram of a vanadium redox flow battery.

200-kW, 800-kWh output leveler, Huxley Hill Wind Farm, King Island, Tasmania [9]
250-kW, 2-MWh load leveler, Castle Valley, Utah

13.5.5 OTHER

Other types of batteries are made of metal-air, Ni-Cd, Zn-Br, and even organic compounds. The metal-air batteries could be less expensive; however, they are at the preproduction stage at which the consumed metal is mechanically replaced and processed separately. Recharge using electricity is under development, but they only have a life of a few hundred cycles and an efficiency of about 50%.

A Zn-Br battery has two different electrolytes that flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. Battery systems are available on transportable trailers (storage plus power electronics) with unit capacities of up to 1 MW, 3 MWh for utility-scale applications. Now, 5-kW, 20-kWh systems are being installed by electric utilities for community energy storage.

General Electric has a sodium halide battery for utility, telecommunication, and UPS applications.

A Ni-Cd battery system (40 MW, 7 min) was installed in Fairbanks, Alaska. Small rechargeable Ni-Cd and lithium ion batteries are available. Should you buy these or continue to buy one-time use batteries for your electronics?

13.6 OTHER STORAGE SYSTEMS

Inductors (from current in coils of wire) store magnetic fields, and capacitors store electric fields from charges, so both can be used to store energy. Their advantages are fast response time and large number of cycles; however, they are presently not used for storing a large amount of energy.

13.6.1 MAGNETIC SYSTEMS

Superconductor magnetic energy storage (SMES) is the stored energy in the magnetic field due to flow of DC in a superconductor. When a superconductor is cooled below the critical temperature, there is no resistance, so there is essentially no energy loss over time. SMESs have long life, fast response, essentially no energy loss over time, and cycle efficiency of 95%; however, temperatures are very low, so there is the high cost for refrigeration and for the superconducting wire. High-temperature superconductors, defined as temperatures of liquid nitrogen (77 K) and above, are now commercially available, and there is much research on materials for very-high-temperature superconductors.

The amount of stored energy is

$$E = 0.5 * L * I^2, \text{ J} \tag{13.4}$$

where L is the inductance (henrys), and I is the current (amperes). The inductance depends on the shape of the coil of wire, which is solenoid or torus. See introductory physics books for information on the calculation of inductance.

There are commercial SMESs, 1-MW units, for power quality control in installations around the world, especially to provide clean power quality at manufacturing plants. There are several larger test projects to provide grid stability in distribution systems; for example, in northern Wisconsin, distributed SMES units enhance the stability of a transmission loop. Superconductors are now being considered for high-power transmission lines.

13.6.2 CAPACITORS

Capacitors are devices for storing charge on two plates separated by some distance, and the amount of stored charged can be increase by placing a dielectric between the plates. One problem with capacitors for energy storage is the leakage current. Electrochemical capacitors (ECs) store electrical energy in the electric double layer, which is formed between each of the electrodes and the electrolyte ions. The amount of stored energy is

$$E = 0.5 * Q^2/C \text{ or } 0.5 * C * V^2 \text{ or } 0.5 * Q * V, \text{ J} \qquad (13.5)$$

where Q is the charge (coulombs), C is the capacitance (farads), and V is the voltage (volts).

ECs have fast response, long life (up to 1 million cycles), and higher energy density than electrolytic capacitors but less than batteries. Aqueous capacitors have a lower energy density due to lower cell voltage; however, they cost less and have a wider temperature range. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones and have lower leakage current.

ECs have been used in conjunction with batteries in hybrid vehicles.

13.6.3 PHASE CHANGE MATERIALS

In a phase change (gas-liquid-solid), there is heat absorption/release at almost constant temperature. For energy storage, the liquid-solid phase change is the only practical one, and the material should have large latent heat and high thermal conductivity [10]. Phase change materials store 5 to 14 times more thermal energy per unit volume than conventional storage materials (water, masonry, and rock). There are a large number of phase change materials in the temperature range from –5°C to 190°C. Organic materials such as paraffin and fatty acids have phase changes in this range. Some problems with using phase change materials are stability of thermal properties under extended cycling and sometimes phase segregation and subcooling.

The heat of fusion for water is 333.6 kJ/kg or 319.8 MJ/m^3. Remember, the density of ice is less than that for water, so containers have to have room for expansion for water in the solid phase. An example of phase change storage for an office building was ice made in the winter, stored in an underground reservoir, and then used for cooling during the summer.

13.6 HYDROGEN

There is a lot of information on hydrogen as the fuel of the future and on the storage of hydrogen [11, Chap. 11, Hydrogen Storage]. Even though hydrogen has a low environmental impact and can be produced by renewable energy sources, the major disadvantage is the low energy density per volume; hydrogen has one-third the energy content of methane. However, existing natural gas pipelines could carry about the same capacity because the hydrogen has lower viscosity.

Fuel cells are much more efficient than internal combustion engines; however, the infrastructure for fuel cell cars is at the nascent stage. So, if hydrogen is produced by renewable energy systems through electrolysis or through bioenergy, then transportation and storage become major factors. Hydrogen can be stored as compressed gas or liquid (must be cooled to 20 K in nonpressurized containers) or by an extraction process. The storage in materials could be adsorption, such as by activated carbon; chemical compounds; compounds that can be reversibly transformed into another substance of higher hydrogen content; and metal hydrides that change hydrogen content with temperature.

Metal hydrides could be used for storage of hydrogen for vehicles powered by fuel cells; for comparison, 100 kg of hydride could store around 500 MJ. However, 100 kg of gasoline provides 4,700 MJ of energy, which is a large difference. The efficiency of the hydrogen fuel cell is around 60%, and for the gasoline engine, it is around 20%. Hydrogen would have fewer emissions and is essentially nondepletable. The production of hydrogen from water using wind and sun would be a problem in arid and semiarid areas where there is already a lack of water. Some considerations for hydrogen storage systems are the following:

Ratio of mass of hydrogen to overall mass of the storage and retrieval system
Ratio of mass of hydrogen to total volume of the storage and retrieval system
Cycle efficiency
Retention (amount of hydrogen remaining over a long period of time)

Of course, as with other storage systems, economics (installed cost, operation and maintenance costs, replacement costs) are paramount, and then there is safety, ease of use, and infrastructure for transportation.

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RECOMMENDED RESOURCES

LINKS

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Energy storage systems. http://www.sandia.gov/ess.

R. B. Schainker. 2008. Emerging technologies to increase the penetration and availability of renewables: energy storage–executive summary. http://www.energy.ca.gov/2008_energypolicy/documents/2008-07-31_workshop/presentations/Energy_Storage-Schainker.pdf.

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PROBLEMS

1. How much energy could be delivered from a pumped hydro reservoir that is 5 million m^3 with a 250-m head? Reduce the amount due to an 80% efficiency.
2. Compare kinetic energy storage to batteries in terms of energy density and installed costs. Both systems have the same amount of energy storage.
3. Find any commercial SMES; note the source, company, and any other useful specifications. How much energy can it store?
4. Find any commercial flywheel for UPS; note the source, company, and any other useful specifications. How much energy can it store?
5. Find any commercial chemical capacitor storage system; note the source, company, and any other useful specifications. How much energy can it store?
6. High-speed flywheels are made from composite material. A flywheel is a ring: 3-m radius, mass = 50 kg, 20,000 rpm. How much energy is stored in the flywheel?
7. Estimate the energy stored in the CAES in McIntosh, Alabama. What is the cycle efficiency of that system?
8. Pick any 12-V car battery. How much energy does it store? Note the brand, specifications of the battery, cost, and expected lifetime.

9. What is the cost per kilowatt hour for a 12-V car battery used for lights and radio? Recharge once per week at a central charging station; life = 2,000 cycles. Cost of a recharge is around \$1.00.
10. What are the advantages of a flow battery versus a deep-cycle lead-acid batteries for energy storage (load level) for a utility?

For problems 11–13: A renewable energy village power system has 10-kW wind, 2-kW PV, 10-kW inverter, and battery bank (24 V, 2,000 Ah). The village is in a good solar and wind resource area, and energy consumption is around 300 kWh/month.

11. Estimate annual energy production and then daily energy production.
12. Estimate the installed cost for a remote area a 2-day drive from a large town over rough terrain. Get information from the Internet on equipment costs.
13. A battery bank can be discharged to 50%. How many days can the battery provide power if there is no wind and no sun?
14. Calculate the cost per kilowatt hour for a D-cell battery for a flashlight (nonrechargeable; 1.5 V, 12 Ah, cost \$4.00).
15. Compare cost per kilowatt hour for alkaline, nonrechargeable AA batteries with lithium ion rechargeable batteries. Alkaline batteries: 1.5 V, 3 Ah, \$0.75. Lithium ion batteries: 1.2 V, 2.2 Ah, \$6.50. Charger cost is \$15, 50% efficient, grid electricity at \$0.10/kWh; lithium ion life is 1,000 cycles.
16. A building uses the latent heat of the change of ice to water for cooling. How much energy can be absorbed in ice to a liquid if originally 500 m^3 of water was frozen?
17. A greenhouse uses a phase change for storage; the tank contains 6,000 kg of paraffin, the melting temperature range is 48–60°C, and latent heat is 190 kJ/kg. How much energy was stored during the phase change?
18. Estimate the capital cost for pumped hydro storage today. Note specifications for reservoir size and head.
19. What are the major problems for using hydrogen for energy storage?
20. Find information on any prototype car powered by fuel cells. What is the fuel source?
21. Compare capital costs per kilowatt or capital costs per kilowatt hour for energy storage systems: pumped hydro, flywheels, lead-acid batteries, vanadium-redox flow battery, and hydrogen in metal hydrides.

14 Institutional Issues

14.1 INTRODUCTION

The institutional issues (this is a noninclusive list as there are surely others) related to renewable energy include the following: legislation and regulation concerning the environment, incentives, externalities, world treaties and country responses to greenhouse gas emissions, connection to utility grids (large power generators such as wind farms, large photovoltaic [PV] arrays, concentrating solar power [CSP]; large numbers of small systems; distributed and community systems); incentives such as feed-in tariffs, renewable portfolio standards, rebates, tax credits; and certification standards for equipment and installation of systems. Of course, most of these issues are determined by politics and economics.

The following are some institutional and environmental issues by resource:

Solar, CSP: large land use for collectors, but land generally low productivity for other uses

Wind: visual, noise, and wildlife, primarily birds (avian) and bats

Bioenergy: large land use for growth of biomass, erosion, burning of biomass releases nitrogen oxides, release of methane

Geothermal: subsidence, seismic activity, reduction of hot springs

Hydro: visual, change in hydrology, impact on fish, large area and removal of people, silt, even dam collapse

Ocean: reduction of tidal flats, marine life, shipping hazard for wave systems, and offshore wind

14.2 UNITED STATES

The U.S. National Energy Act of 1978 was a response to the 1973 energy crisis. The main purpose was to encourage conservation of energy and the efficient use of energy resources. The Public Utility Regulatory Policies Act (PURPA) covers small power producers and qualifying facilities (independent power producers), which are up to 80 MW. Sections 201 and 210 of PURPA encourage the use of renewable energy by mandating the purchase of power from qualifying facilities and exempting such facilities from much of the federal and state regulations. States had a large amount of flexibility in implementing PURPA. The main aspects of PURPA are as follows:

Utilities must offer to buy energy and capacity from small power producers at the marginal rate (avoided cost) the utility would pay to produce the same energy.

Utilities must sell power to these small power producers at nondiscriminatory rates.
Qualifying facilities are entitled to simultaneous purchase and sale. They have the right to sell all their energy to the utility and purchase all the energy needed.
Qualifying facilities are exempt from most federal and state regulations that apply to utilities.

The implementation of PURPA was determined by public utility commissions, utilities, independent power producers, and the courts. Determination of avoided costs was the main point of contention between small power producers, independent power producers, and utilities.

The National Energy Strategy Act of 1992 included the provision of wheeling power over utility transmission lines. The Federal Energy Regulatory Commission (FERC) can order the owner of transmission lines to wheel power at costs determined by FERC. The utilities are allowed to recover all legitimate, verifiable economic costs incurred in connection with the transmission services and necessary associated services, including, but not limited to, an appropriate share, if any, of the costs of any enlargement of transmission facilities. From the standpoint of wind power, this legislation is important because the major source of wind energy is in the Great Plains, which is far from the major load centers. In 1997, FERC opened transmission access. The first wind farm (initial 35 MW, later expanded to 68 MW) in Texas was in the far western part of the state, and power was wheeled to the Lower Colorado River Authority area in central Texas.

The deregulation of the electric utility industry by some states has changed the competition for renewable energy. Deregulation essentially means that the integrated electric utility companies are split into three areas: generation of power, transmission, and distribution. Also, consumers can buy from different power producers. The other aspect for increased use of renewable energy is green power and the push for reduction of pollution and emissions from fossil fuel plants that generate electricity.

The goal of 20% electricity from wind energy by 2030 for the United States will require major institutional changes, primarily in terms of transmission, carbon trading, and development of more load management. The location for much of those wind farms would be in the wind corridor of the Great Plains.

14.2.1 Avoided Cost

The avoided costs were established by the public utility regulatory body in each state. FERC defines avoided cost as the incremental or marginal cost to an electric utility of energy or capacity, which the utility would have to generate or purchase from another source if it did not buy power from the qualifying facility. Avoided cost reflects the cost from new power plants, not the average cost from plants already installed. However, many utilities said they did not need any new generation; therefore, avoided costs were only the fuel adjustment cost. The avoided cost includes not only present but also future costs.

Utilities can set a standard purchase rate for qualifying facilities under 100-kW capacity, and local public regulatory bodies can provide more information on small power production. In the 1980s, the California Public Utilities Commission (PUC) set the avoided costs and types of contracts for qualifying facilities. Standard Offer Number 4 set the avoided costs for a period of 10 yr, while Standard Offer Number 1 was variable depending on the cost of fuel. One of the reasons wind farms started in California was the high avoided costs set by the PUC.

Some utilities state that they have excess capacity, and therefore the avoided cost is equal to the value of the cost of fuel at the power plant. The fuel adjustment cost for Southwestern Public Service in the Texas Panhandle in January 1994 was $0.02/kWh. The company was consolidated with a company in Colorado and Minnesota, now called Xcel Energy; however, in 2010 the avoided cost in this region was still the fuel adjustment cost, which was around $0.025/kWh, although when natural gas prices were high, the avoided cost was larger, depending on the percentage mix of natural gas for boiler fuel. However, the changing natural gas prices had utilities considering wind as a hedge against future volatility of natural gas costs, and some utilities were requesting proposals for wind farms for their systems.

14.3.2 UTILITY CONCERNS

For low penetration of renewable power generators, which produce variable power, on a large utility grid there would be no problems with that small amount of power. It would be considered as a negative load: a conservation device, which is the same as turning off a load. For large penetration, 20% and greater, other factors such as the variability and dispatching become important. Also, operation and maintenance (O&M) costs could increase for conventional generators as they have more variable output, which could increase O&M costs due to variable renewable energy input to the grid. The utilities are concerned about safety and power quality due to any systems on their grid.

Safety is a primary consideration for any renewable energy project, just as with any other industrial enterprise. All energy industries have safety concerns, for example, underground coal mines or the drilling for natural gas in shale formations.

For large and small systems that generate electricity and are connected to the grid, primary concerns are energizing a dead utility line, grounding of equipment, and lightning. For wind turbines, high voltages, rotating blades and machinery, large weights, and working at hub heights up to 100 m make for a hazardous workplace. There is a summary and a list of accidents for the wind industry, including type of accident, turbine, date, and location [1]. In the survey, the longest recorded distance for blade failure was 400 m from the tower. The largest number of accidents was from blade failures, the second largest was from fire; the most common fatality was from falls. Now, large wind turbine failures make news, and the videos appear on the Web.

A mortality rate of 0.4 deaths/MWh is reported for the mid-1990s, which dropped to 0.15 deaths/MWh by the end of 2006 [2]. Some of the deaths in the database were associated with the transport of wind turbines. The mortality rate for any renewable energy industry needs to be compared to those of other conventional energy industries.

Quality of power refers to harmonics, power factor, voltage, and frequency control. A number of renewable energy systems on the end of a feeder line could require extra equipment to maintain quality of power. However, PV could increase the power quality and reliability on feeder lines as they supply power during peak air conditioning loads. Utility companies have to supply reactive power for induction generators for wind turbines, and they may require capacitors on the wind turbine or at the wind farm substation to maintain the power factor.

Connection of any renewable energy-generating system to the grid must be approved by the utility. The utility should be informed at the earliest possible stage of the intention to connect a renewable energy power source to its system. Information for the utility should include

Specifications of the renewable energy system
Schematic (block diagram) of the electrical system
Description of machine controls when there is loss of load (utility power) and a lockable disconnect

The utility may require a meter that measures flow of energy in both directions, even if there is net energy billing. Smart meters for demand side management will be installed in more locations as the national grid is transformed and would make the energy from distributed renewable energy systems more valuable.

For large systems (10 MW and up), an interconnection study will cost from $30,000 to $120,000. This study determines the effect of the renewable energy system on the transmission lines and existing generators.

Liability for damage is another concern of utilities. The utilities would like to be insured against all damage due to the renewable energy system operation. Of course, the small power producer would like to be insured against damage to their system as a result of utility operation; however, that is impossible to obtain. For small systems, insurance should be available as part of a homeowner's policy or as part of a business policy. Some electric cooperatives were requiring proof of a $500,000 liability policy for connection of a wind turbine to their system.

Ancillary costs are those costs to the utility as renewable energy systems become a larger percentage of the generation capacity on the grid. The variability of renewable energy systems can increase operating costs, such as committing unneeded generation, scheduling unneeded generation, allocating extra load-following capability, violation of system performance criteria, and increasing cycling operation on other generators. Estimates of these costs range from $0.001 to $0.005/kWh [3]; however, one utility estimated the cost at $0.0185/kWh. In 2008, the Montana Public Service Commission set a rate up to $.00565/kWh for integration of wind power from the Two Dot wind farm into the utility grid.

A major storm occurred in Spain with winds above the cut out wind speed, which resulted in a major drop in output from 7,000-MW wind farms compared to the predicted input to the utility grid operation for that day. In another case, wind farms produced 53% of the total demand in Spain for 5 h (November 2009) when there was ample wind and low demand on the grid during early hours of the day.

14.3 REGULATIONS

Regulations for renewable projects vary by country and by region or state, from simple (e.g., a review process from a single agency), to multiple (e.g., complex reviews for different agencies), and even to multiple levels of government. Sometimes, there seem to be competing regulations from different agencies, and the number of agencies can be large. National laws and policies may restrict connection of any renewable energy system to the utility grid. Most large projects require consideration of environmental impact, although actually enforcement may vary widely, depending on the country.

In the United States and other developed countries, permits for construction are generally required in residential areas and even in rural areas in some states. Zoning issues are esthetics (primarily visual), safety, and, for wind turbines, tower height, setbacks, and noise. Risks are accepted from other areas, such as cars, utility lines (electric and gas), and so on. Signs, trees, and even utility poles have failed in high winds or under conditions of icing.

Restriction of access and signs for high voltage are needed for renewable energy systems that generate electricity. One factor can never be dismissed: Anything that interferes with TV will be unacceptable to the public. Most locations do not have specific zoning regulations for renewable energy systems, so individuals must be prepared to educate public boards and their neighbors, although that is now changing as more systems are being sold due to availability of tax credits for small renewable energy systems.

In the United States, federal permitting requirements range from environmental to Federal Aviation Administration regulations on lights for tall towers and wind turbines (lights on towers or turbines taller than 200 ft). Those in the industry maintain that regulations are now a major portion of their cost of doing business. In most cases, those in the industry say that they cannot meet proposed regulations because it is uneconomical.

14.4 ENVIRONMENTAL ISSUES

There will be environmental issues for any large renewable energy project; the issues will vary by the renewable energy resource and the location, and there may even be environmental issues for small installations up to 100 kW. So, those developing projects should be prepared to have an environmental impact study or at least be able to obtain information as the Environmental Protection Agency has jurisdiction over many aspects. What is the biological impact on wildlife, plants, and habitat? Another common aspect is the visual impact, which can be detrimental, especially in those areas that are located close to scenic areas or parks. Some may like the view of large numbers of wind turbines, and others will be opposed. At the end of the project, decommissioning, recycling, and disposal, especially of any toxic components, have to be considered. The goal of the U.S. Fish and Wildlife Service is to protect wildlife resources, streamline site selection, and assist in avoiding environmental problems after construction. A U.S. Fish and Wildlife Service report addressed how to minimize the impacts of land-based wind farms on wildlife and its habitat [4].

There will be land areas that are excluded because of environmental considerations: national and state parks, wetlands, and wild life refuges. In addition, some states and even counties have regulations concerning the environment that will have to be met before a project can be considered. First, check with local officials before you install any system.

The developer should conduct an analysis of the environment regarding permits, licenses, and regulatory approvals; threatened or endangered species; wildlife habit; avian and bat species; wetlands and other protected areas; and location of known archeological and historical resources. Geographical information systems are an excellent tool for depicting environmental and land use constraints. Regulations on archeological sites differ by state, and in some states, private land is excluded. Even if it is not mandatory to check for archeological sites, it probably still should be done for a project of medium size and larger.

After the first analysis of environmental issues, a more detailed analysis should address possible impacts and possible mitigation of those impacts. After the project is operational, mitigation of the impacts has to be monitored on a scheduled basis. Biological concerns are habitat loss, alteration or fragmentation of habitat (e.g., prairie chickens), bird or bat collisions with wind turbines, electrocution of raptors, and effect on vegetation. Water, especially wetlands, soil erosion, and water quality have to be considered. For wind farms, the clearing of scrub brush for roads, sites, and even for laying underground wires is welcomed by ranchers; however, the cleared areas, such as shoulders of the roads, have to be seeded and monitored for growth, erosion, and noxious weeds. Another possibility in complex terrain and even range areas is that maintained roads may be welcome by the land owner or operator, and the roads can serve as firebreaks.

For protection against liability, a developer should perform a screening and environmental assessment prior to or early in the acquisition of the property. The American Society for Testing and Materials has screening tools and standards for environmental site assessment [5].

Some people are adamantly opposed to almost any large energy project in their vicinity, including those for renewable energy. In general, most individuals are neutral, and the rest are in favor, especially those who will receive some economic benefit. In the Great Plains of the United States, there is less opposition as wind farms are seen as rural economic development. Developers should provide community education at the planning and preconstruction phases of a project.

Wind farms are now a large renewable energy resource, so the environmental impacts of visual, noise, and birds and bats will be considered in more detail as an example.

The visual impact for wind farms is quite different because the number and height of the towers as wind turbines will be visible from 20 km. In the plains, they are visible from all angles (Figure 14.1), with only the curvature of the Earth limiting the distance from which they can be seen. In mountainous areas, the wind turbines will be in lines on the ridges, but in general they are not visible from all angles because most of the roads are in the valley. The moving rotors make wind turbines more noticeable, and flashing lights make them conspicuous at night, especially when the lights are synchronized to outline the wind farm. Shadow flicker happens, and the high impact is generally located within approximately 300 m of the turbine. In a

FIGURE 14.1 Visual aspect of wind turbines near Hitchland, Texas, looking south. Foreground: 3.2 km to one turbine, Vestas V 90, 3 MW, diameter = 90 m, 80-m tower; middle left, 4.4 km to row of eight Suzlon wind turbines, 1.25 MW, diameter = 64 m, 72-m tower; background, John Deere 4 wind farm, 9.5 km to first row, 14.5 km to back row, 38 Suzlon wind turbines, 2.1 MW, diameter = 88 m, 80-m tower.

pasture with no trees in the summertime, yearling calves and even horses line up in the shadows of the tower of the wind turbines, and the animals move to keep in the shade as the tower shadow moves.

Noise measurements have shown in general that wind turbine noise is below the level of ambient noise; however, the repetitive noise from the blades stands out. In general, one would not want a residence in the middle of a wind farm. The whine from gearboxes on some units is also noticeable. However, with larger wind turbines at higher hub heights and new airfoils, the noise has been much reduced. The farmers who live close to the wind turbines at the White Deer wind farm reported that noise was not a problem, especially since they were receiving money for the wind turbines on their land. Others near wind farms who are not receiving any economic benefit exaggerate the noise level, comparing it to jet engines on planes.

Birds and bats can be killed by wind turbines as the tips of blades for both small and large wind turbines are moving around 70 to 80 m/s. The factors for mortality of birds and bats are number of fatalities, bird species, season, the threat to the population, and possible forms of mitigation. Collision rates for birds per turbine per year vary from 0.01 to 23 for a coastal site in Belgium, where the birds included gulls, ducks, and terns. Other coastal sites in northwest Europe had a rate of 0.01 to 1.2 birds per turbine per year. However, neither of these examples produced a significant decline in population. In general, migratory birds fly above the heights of wind turbines; however, overcast and ground clouds may lower flight paths. Two large wind farms, south of Corpus Christi, Texas, near the coast, have a radar for monitoring migration of birds, and the wind turbines are shut down if they pose a threat to the birds. Note that hundreds of thousands of birds are killed by communication towers, buildings (Geographica, photo in *National Geographic*, September 2003), hunters, and even cars.

After bats became a problem in West Virginia, information and guidelines became available for both bird and bat impacts [6–8]. One report stated that the air pressure differential of the passing blades could affect bats; it did not have to be a direct strike from the blade. Preconstruction data are used for predicting fatalities, and that projection needs to be compared with bird or bat fatalities after the wind turbines are operating.

Similar institutional and environmental problems will be associated with other renewable energy projects. Identification of problems, mitigation, and continued monitoring are essential.

14.5 POLITICS

As with any endeavor, politics enters the situation. To make a change in behavior of people and institutions, especially when the competition is an entrenched industry, you need *incentives*, *penalties*, and *education*. Someone estimated that the amount of each type of energy used is in direct proportion to the amount of subsidies in the past for that type of energy. Subsidies are in the form of taxes, tax breaks, and regulations, all of which generally require legislation: politics. What every entity (industry) wants are incentives for itself and penalties for its competitors. In addition, these entities want the government to fund research and development (R&D) and even commercialization.

Incentives are tax breaks, subsidies, mandates, and regulations to promote R&D and commercialization. Public utility commissions are demanding that utilities use integrated resource planning (IRP), which means they have to consider renewable energy and conservation in the planning process. Can utilities make money for kilowatt hours saved? Who is supposed to take the risk, the consumers or the shareholders? Three Mile Island and the nuclear utility industry are good examples of politics, from the local to national level. The Price Anderson Act, a federal law, limited the amount of liability from a nuclear accident, and without that legislation, the nuclear industry could not have sold plants to utilities.

Penalties are generally in the form of taxes and regulations. Environmental groups have already indicated that utilities will be held accountable for the risk of a carbon tax if they plan on new coal plants. In other words, in their opinion the shareholders and not the consumers should take the risk.

Education is public awareness of the possibilities or options, a realistic cost–benefit comparison over the lifetime of the energy systems. Remember that you cannot fool Mother Nature, and you will pay one way or another; you will probably pay more later if the problem is not taken care of in the present.

Politics will continue to influence which and how much different energy sources are subsidized. Some incentives, or some may see them as penalties, include carbon trading or a carbon tax, rebates on equipment or incentives for electrical energy produced from renewable energy, renewable portfolio standards (renewable electric standards), feed-in tariff for renewable energy, and others.

14.6 INCENTIVES

Energy subsidies have serious effects, generally in favor of conventional fossil fuels and established energy producers. Subsidies for renewable energy between 1974 and 1997 amounted to $20 billion worldwide. This amount can be compared with the much larger subsidies for conventional energy sources, which totaled *$300 billion per year*, and this number does not even take into account the expenditures for infrastructure, safeguards, and military actions [9] for continued flow of oil and natural gas. The privatization of the electric industry along with the restructuring into generation, transmission, and distribution has opened some doors for renewable energy.

In the support of national and state policies, the common tax incentives for renewable energy [10] are as follows:

Investment tax incentives: Large-scale applications provide income tax deductions or credits for some fraction of the capital investment.

Investment tax incentives: Residences and businesses receive tax deductions or credits for some fraction of the costs of renewable energy systems.

Production tax incentives: Provide income tax deductions or credits at a set rate per kilowatt hour.

Property tax reductions.

Value-added tax (VAT) reductions: Exempt producers of renewable energy from taxes on up to 100% of the value added by an enterprise between purchase of inputs and sale of outputs.

Excise (sales) tax reductions: Exempt renewable energy equipment purchasers from up to 100% of excise (sales) tax for the purchase of renewable energy or related equipment.

Import duty reductions.

Accelerated depreciation: Allows investors to depreciate plant and equipment at a faster rate than typically allowed, thereby reducing stated income for purposes of income taxes.

Research, development, demonstration, and equipment manufacturing tax credits.

Tax holidays: Reduce or eliminate income, VAT, or property taxes for a temporary period of up to 10 yr.

Taxes on conventional fuels: Some countries tax the consumption of nonrenewable energy (most often a fossil fuel or carbon tax).

Mandates for manufacturing: percentage of components that must be made in country. In China, wind turbines installed in the country must have 70% of the components made in China. The American recovery and reinvestment act has a buy America provision.

14.6.1 UNITED STATES

The Database of State Incentives for Renewable Energy (DSIRE) is a comprehensive source of information on state, local, utility, and selected federal incentives that promote renewable energy and energy efficiency [11]. Overview maps are also available by type of incentive and policies. Check the database for detailed information.

The major impetus to the wind and the concentrating solar power industries was due to federal tax credits, the National Energy Act of 1978, and the avoided costs set by the California PUC. The credits for wind expired in 1985, while the solar credits were continued.

The second major impetus for the wind industry was the renewable energy production tax credit (PTC). The PTC was part of the National Energy Strategy Act of 1992, and it provides a \$0.015/kWh incentive for production of electricity by renewable energy. A commercial or industrial entity can claim the PTC under Section 45 of the Internal Revenue Service code. The provisions are as follows:

The investor owns the wind facility, which was placed in service during the period December 31, 1993, to July 1, 1999.
The investor produces the electricity at the facility.
The investor sells the electricity to an unrelated party.

The credit applies to production through the first 10 yr of the operation of the facility. The credit is intended to serve not only as a price incentive but also as a price support. The credit is phased out as the average national price exceeds \$0.08/kWh, based on the average price paid during the previous year for contracts entered into after 1989. Both values are adjusted for inflation. The credit can be carried back for 3 yr and carried forward for 15 yr to offset taxes on income in the other years. The eligible technologies are landfill gas, wind, biomass, hydroelectric, geothermal electric, municipal solid waste, hydrokinetic, anaerobic digestion, small hydroelectric, tidal, wave, ocean thermal.

The PTC has been extended a number of times and is now available through 2013. In 2010, the PTC was \$0.021 for wind, geothermal, and closed-loop biomass technologies and \$0.011 for the other technologies. Some technologies are only eligible for 5 yr.

Because of the problem of finding an entity with available tax liability, as part of the American Recovery and Reinvestment Act the developer can choose to receive a 30% investment tax credit (ITC) instead of the PTC for facilities placed in service in 2009 and 2010 and for facilities placed in service before 2013 if construction begins before the end of 2010. The ITC then qualifies to be converted to a grant from the Department of Treasury. The Treasury Department must pay the grant within 60 days of application submission.

The renewable energy production incentive was similar to the PTC, except the eligible entities were local government, state government, tribal government, municipal utility, rural electric cooperative, and native corporations. The problem was the amount of funding was capped, and Congress had to approve funding every year, so few projects were constructed that used this incentive.

Small renewable energy systems with 100 kW of capacity or less can receive a tax credit for 30% of the total installed cost of the system. This tax credit (Emergency Economic Stabilization Act of 2008) is available for equipment installed from October 3, 2008, through December 31, 2016. The value of the credit is now uncapped through the American Recovery and Reinvestment Act of 2009.

Federal and state incentives encourage ethanol production [12], for example, the mandates and incentives of the Energy Policy Act of 2005. Gasoline was mandated to contain 7.5 billion gallons of renewable fuel annually by 2012, and most of the requirement will be met with ethanol. The Energy Independence and Security Act of 2007 increases renewable fuel use to 36 billion gallons by 2022. The act requires advanced biofuels, which are defined as fuels that cut greenhouse gas emissions by at least 50%. The advanced biofuels could include ethanol derived from cellulosic biomass, biodiesel, butanol, and other fuels. The Volumetric Ethanol Excise Tax Credit amounts to around \$0.45/gal subsidy for ethanol.

For PV, California has significant feed-in tariffs and investment subsidies:

Systems > 100 kW_P: \$0.39/kWh
Systems < 100 kW_P: Can choose either \$2.50/W_P or \$0.39/kWh
Contract duration: 5 yr, constant remuneration
Net metering: up to 2.5% of peak demand, rolls over month to month, granted to utility at end of 12-month billing cycle

Many states offer rebates for renewable energy systems, from a flat rate of \$500 to \$4/W installed.

14.6.1.1 Federal Support

The federal government continues to support renewable energy through the Department of Energy (DOE) budget for Energy Efficiency and Renewable Energy (EERE). For more detailed information, visit the to EERE Web site (http://www.eere.energy.gov, then scroll to About EERE>Budget). As always, the DOE budget for renewable energy is less than the budget for nuclear energy.

As an aside, every president from Nixon to today and most politicians have touted energy independence. It is interesting to note that there are generally one to two energy acts per president, but neither any president nor Congress has taken the necessary steps to implement energy independence because it would require major sacrifices and some changes in lifestyle, and it is tough to get elected or reelected on those premises.

The tone or direction of energy policy is set by the administration, which changes with the president. The early direction was R&D plus demonstration projects, which was supposed to lead to commercialization. During the Reagan years, private industry was supposed to commercialize renewable energy, and federal funding was for generic R&D. During Reagan's term, the support for renewable energy was reduced every year.

Under Clinton, there was renewed interest in renewable energy, and the direction was commercialization. The Climate Change Action Plan moved the DOE from focusing primarily on technology development to playing an active role in renewable energy commercialization. This initiative was backed up with \$72 million for fiscal year 1995 and a total of \$432 million through the year 2000. For the emissions reductions from renewables, the DOE looked primarily to wind since it was the most economical renewable source at that time.

Under George W. Bush, the national energy plan first focused on increased production of oil and gas. With pressure from Congress, conservation, energy efficiency, and renewables were added to the package, and the PTC was extended in 2002. However, an increase in vehicle efficiency, CAFE (combined automobile fleet efficiency) standards, did not pass. Another national energy act, the Energy Policy Act of 2003, was passed, and finally CAFE was increased in the last year of the Bush administration.

President Obama has changed the direction dramatically toward renewable energy, which means every university and national lab will be seeking that money by creating renewable institutes and centers. It would be interesting to count the number of new degree programs, institutes, and centers at universities during the past 3 to 4 yr.

14.6.1.2 State Support

States are also competing for renewable energy as a way to offset importation of energy and as a way to create jobs. Some states have mandated deregulation of the electric utility industry. Deregulation in some states gives the consumers choice of producers, and most of the states have a system benefits charge (SBC) that lets utilities recover stranded costs of power plants, primarily for nuclear plants. In some states, part of the SBC is set aside for renewable energy. For example, in California, funds from the SBC are available to offset part of the cost for small renewable energy systems.

The wind farm boom in Texas was fueled by a renewable portfolio standard (RPS) enacted in 1999, which was part of electric restructuring legislation. The mandate was for 2,000 MW of new renewables by 2009 in the following amounts by 2-yr steps: 400 MW, 2003; 450 MW, 2005; 550 MW, 2007; and 600 MW, 2009. There was rapid growth of wind farms in Texas, and now many states have an RPS. Texas expanded the RPS in 2000 with a new goal of 5,880 MW of renewables by 2015, with a carve-out of 500 MW to come from nonwind sources. Texas easily surpassed this goal as around 10,000 MW of wind power were installed by the end of 2010. The legislators and even utilities were surprised at the amount of wind capacity that was installed as a result of the RPS and the national PTC.

Another aspect of the electric restructuring in Texas is that electric retailers have to acquire renewable energy credits (RECs; 1 REC = 1 MWh) from renewable energy produced in Texas or face penalties of up to $50/MWh. Anybody may participate in the REC market: traders, environmental organizations, individuals, and so on. The market opened in January 2002, and early prices were around $5/REC, but due to the large amount of wind power installed, in 2009 the value was around $3/REC. The RECs are good for the year created and bankable for 2 yr.

As always, industries seek tax breaks at every level. States and local entities give tax breaks for economic development, and renewable energy developers would like a tax break on installed costs as that is their major cost. Conventional power producers can deduct the cost of fuel, whereas for renewable energy these deductions are not available since the fuel is free. Legislators are now touting renewable energy, especially as rural economic development. States and development commissions are trying to lure businesses in renewable energy.

14.6.1.3 Green Power

For green power, the consumer pays a voluntary premium, which is around $3/month for a 100-kWh block, or contributes funds for the utility to invest in renewable energy development. Green power is an option in the policy in some states and has been driven by responses of utilities to customer surveys and town meetings. Green power represents a powerful market support for renewable energy development, which was mainly wind energy and ethanol. More than half of all U.S. electricity customers have an option to purchase green power from more than 750 utilities or about 25% of utilities nationally [13]. Some utilities have lowered the rate premium on green power as traditional fossil fuel costs have increased. As green power becomes cheaper than regular power, will those consumers who purchased green power pay below the regular rate? The National Renewable Energy Laboratory (NREL) ranks the utility green power programs annually.

14.6.1.4 Net Metering

Forty-three states have net metering (Figure 14.2), which ranges from 10 to 1,000 kW, with most in the 10- to 100-kW range. If the renewable energy system produces more energy than is needed on site, the utility meter runs backward, and if the load on site is greater, then the meter runs forward. Then, the bill is determined at the end of the time period, which is generally 1 month. If the renewable energy system produced more energy over the billing period than was used on site, the utility company pays the avoided cost. In some states, any net to the consumer is carried over to the next month or the payment time period, and at the end of the year, any net production accrues to the utility with no payment to the consumer.

In general, net metering in the 10- to 50-kW range did not increase the sale of renewable energy systems since the electricity produced was still not cost competitive with retail electricity. If a small renewable system is installed, you want to use that energy on site as that is worth the retail rate. Also, if the time period is longer than 1 month or there is rollover for positive production, net metering is more useful to the consumer.

Of course, utility companies do not like net metering because it increases billing problems, and the utilities say that one group of customers would be subsidizing another group of customers. With electric restructuring, utilities are worried that large customers will find cheaper electricity, and then rates will rise for residential customers. Does that mean that many residential customers are subsidized today?

14.6.2 OTHER COUNTRIES

There have been incentives and goals for renewable energy around the world, with more announced every year. The amount of each type of renewable energy installed follows the legislation, regulations, and especially the amount of incentives provided. So far, the major impact has been large-scale installation for wind farms and ethanol plants, with PV and solar hot water making significant contributions. The Internet will have information on renewable energy incentives by country.

The European Union is a leader in the development and installation of renewable energy. The E.U. goal is 20% of energy consumption from renewables by 2020, with some countries setting higher goals. Those in the European Union are even discussing 100% from renewables by 2050. Japan, Spain, and Germany now are big markets for PV, and some countries are also requiring installation of solar hot water.

14.6.2.1 Wind

Several European countries started wind energy programs in the 1980s, with most emphasizing megawatt wind turbines; however, there was little success. The manufacturers in Denmark produced small units, then progressed to larger units in steps,

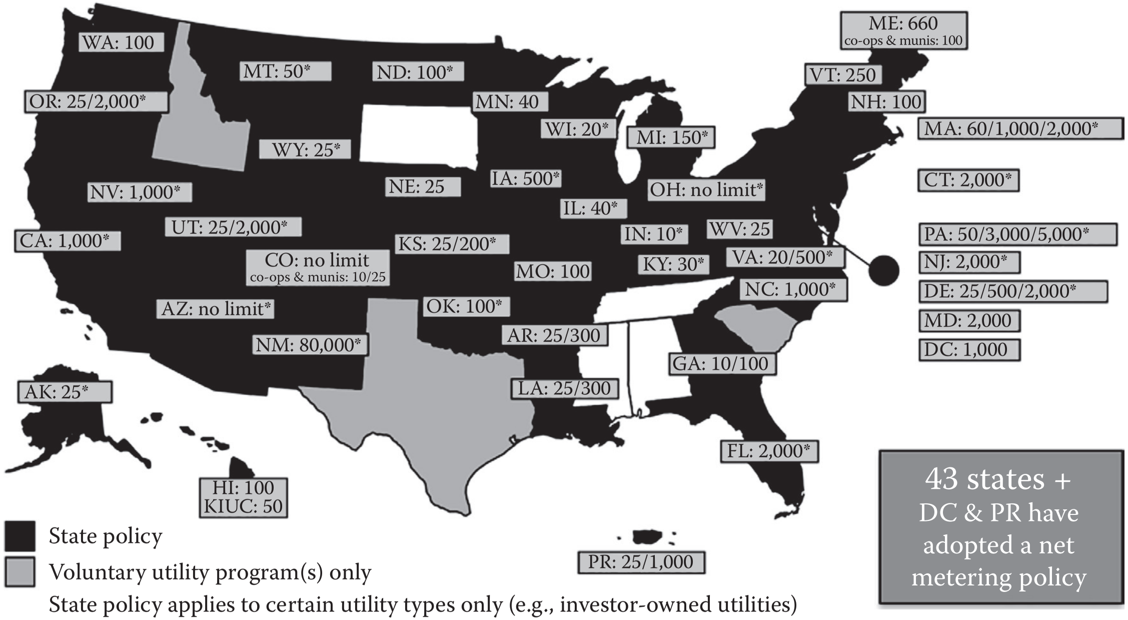

FIGURE 14.2 Map of net metering for the United States. (From the Database of State Incentives for Renewable Energy (DSIRE), http://www.dsireusa.org.)

and acquired around 50% of the early U.S. market and 66% of Europe's installed capacity in 1991. European manufacturers have now captured the major share of the world market.

The different policy options for renewable energy in the E.U. single market were discussed by Krohn [14] and Pollard [15]. Free trade in renewables in the E.U. market is complicated by the fact that renewables are supported by mandates or fixed prices at different levels by country and even state. This support could be regarded as a substitute for a pollution tax on fossil fuels.

Promotion of wind energy in Europe was based on two models: (1) price support for kilowatt hour production and (2) capacity based. In general, the minimum-based price (feed-in tariff) resulted in the most installations. Denmark, Germany, and Spain used the price support method, while the United Kingdom, Ireland, and France use the capacity-based method.

Germany accounted for half the European market for wind after 1995 due to the Electricity Feed Law (EFL, 1990), which was designed for climate protection, for saving fossil fuels, and for promoting renewable energy. The law obliges utilities to buy any renewable energy from independent power producers at a minimum price defined by the government, with the price based on the average revenue of all electricity sales in Germany. The initial value in 1991 was €160/MWh, and then it declined as more wind power was installed. Since the Renewable Energy Sources Act was enacted, electricity generation in Germany from renewable energy doubled from 6% in 2000 to 13% in 2007 [16], and most of that was generated by wind. The EFL was modified in 1998, which set a regional cap of 5% for renewable electricity. Some states also gave a 50% investment grant in the late 1980s and early 1990s. Special low-interest loans for environmental conservation measures were also available for financing projects. These factors contributed to the massive growth of wind in the 1990s in Germany. The law was changed in 2004 to €87/MWh on production for 5 yr and €55/MWh for the next 15 yr. For projects or wind turbines that came online in later years, there was a decrease of 2.5% per year. For example, for 2010, the payment is €79/MWh on production for 5 yr and €50/MWh for the next 15 yr.

China now ranks fourth in the world in installed wind capacity due to favorable government policies for the installation of wind farms. The wind industry has relied on financing through the Clean Development Mechanism (Kyoto protocol), which has presented some problems for new projects. As in other countries, transmission needs to be upgraded from the windy areas to the load centers. Presently, China mandates that 70% of the components of wind turbines erected in China be produced by factories within the country. The feed-in tariff is now around €50/MWh. To meet the goal of 3% of electricity from nonhydro renewables by 2020, 100 GW of wind capacity would need to be installed.

India ranks fifth in the world in installed wind capacity due to a favorable fiscal/policy environment. Wind power development in India has been promoted through R&D, demonstration projects and programs supported by government subsidies, fiscal incentives, and liberalized foreign investment procedures. The incentives are as follows:

Central government: Income tax holiday, accelerated depreciation, duty-free import, energy capital/interest subsidies.

State governments: Buyback, power wheeling, and banking; sales tax concession, electricity tax exemption; demand cut concession offered to industrial consumers who establish renewable power generation units; and capital subsidy. Tamil Nadu and several other state electric boards purchase wind energy at about \$64/MWh.

14.6.2.2 Photovoltaic Energy

Japan, Spain, and Germany are the big markets for PV. The Japanese program started in 1994 with subsidies that were reduced by year to no subsidy in 2003 as more systems were installed. At the end of 2004, Japan led the world in installed PV capacity with over 1.1 GW. Then, in January 2009 Japan restored the subsidy system for domestic PV with grants of \$760/kW.

Europe captured close to 80% of total annual installed PV capacity in 2009, with Germany and Spain leading the way due to substantial feed-in tariffs. Germany started a large-scale feed-in tariff system in 2000, and in 2007 Spain introduced a high feed-in tariff of 32–34 €/MWh. Both Germany and Spain are reducing or capping the amount of subsidy due to the large number of installations.

A government regulation (1980) in Israel requires solar water heating in every new building. Now, 90% of the homes in Israel have solar hot water, and 80% of all the annual water heating requirements is met by solar hot water. This provides a saving of 3% of primary energy use. Now, other countries are mandating solar hot water for new construction. Even in the United States, starting in 2010, Hawaii has a law that every new single-family home must have solar hot water.

The production of ethanol has increased dramatically due to mandates and incentives. In the United States, there is a lot of political support as it is seen as improvement of rural economic income.

14.7 EXTERNALITIES (SOCIAL COSTS/BENEFITS)

Externalities are defined as social or external costs/benefits that are attributable to an activity that are not completely borne by the parties involved in that activity. Externalities are not paid by the producers or consumers and are not included in the market price, although someone at some time will pay for or be affected by them.

Social benefits, generally called subsidies, are paid by someone else and accrue to a group. An example is the Rural Electrification Act, which brought electricity to rural United States. An example of a positive externality (social benefit) is the benefit everyone gets from cleaner air from installation of renewable energy systems. On the other side, a good example of a negative externality is the use of coal in China, as every city of 100,000 and over has terrible smog due to use of coal for heating, cooking, industry, and production of electricity. In 20 yr, there will be a large public health cost for today's children.

External costs can be divided into the following categories:

Hidden costs borne by governments, including subsidies and support of R&D programs

Costs associated with pollution: health and environment damage, such as acid rain, destruction of ozone in the upper atmosphere, unclean air, and lost productivity.

Carbon dioxide emissions may have far-reaching effects, even though global warming is disputed by many in industry and some scientists (http://cdiac.esd.ornl.gov/trends/co2/contents.htm).

Mechanisms for including externalities into the market are government regulation, pollution taxes, IRP, and subsidies for R&D and production.

Government Regulation: The historical approach of regulation or mandates has led to inefficient and monopolistic industries and inflexibility, and it is highly resistant to change. The current vogue is for deregulation and privatization of energy industries. However, if external costs are not included, short-term interests prevail, and this generally distorts the economics toward conventional and entrenched suppliers of energy. Regulations can require a mix or minimum use of energy sources with lowest life-cycle cost, which include externalities.

Pollution Taxes: Governments can impose taxes on the amount of pollution a company generates. European countries have such taxes. Another possibility is to give RECs for producing clean power. Pollution taxes and avoidance of pollution have the merit of simplicity and have only a marginal effect on energy costs but are not a true integration of external costs into market prices. The taxpayer pays, not the consumer. The pollution tax could be assessed in the consumer bill; therefore, it is paid on how much is used.

Integrated Resource Planning: This model combines the elements of a competitive market with long-term environmental responsibility. An IRP mandate from the government would require the selection of new generating capacity to include all factors, not just short-term economic ones.

Subsidies: Of course subsidies for renewable energy promote that source and make that source more competitive with conventional fossil fuels. However, the recipients want the subsidy to continue, problems with timing of subsidy may make for difficult business decisions, and the subsidy may be harmful to an overall long term, rational energy policy.

Many studies on externalities have been conducted. The European Union's six-volume *ExternE: Externalities of Energy* (http://www.externe.info/) is probably one of the most systematic and detailed studies to evaluate the external costs associated with a range of different fuel cycles. In their estimates, external costs for production of electricity by coal can be as high as $0.10/kWh and external costs for nuclear power at $0.04/kWh.

Since 1995, companies in the United States have been trading sulfur dioxide (SOX) and nitrogen oxides (NOXs) emissions, which are precursors of acid rain and contributors to ground-level ozone and smog. Essentially, industries trade in units called allowances, which can be bought, sold, or banked for future use. Carbon

TABLE 14.1
U.S. Generation of Electricity and Air Emissions, 2009 Values

		Carbon Dioxide		Sulfur Dioxide		Nitrogen Oxides	
	MWh 10^6	**Kg/MWh**	**Tons 10^6**	**kg/MWh**	**Tons 10^6**	**kg/MWh**	**Tons 10^6**
Coal	1,764	950	1676	3.0	5.3	1.5	206
Oil	931	710	661	2.7	2.5	0.7	0.6
Natural gas	284	480	136	0.003	0.001	0.6	0.2
Total	2,979		2,473		7.8		3.4

Megawatts per hour and metric tons total from EIA, DOE. Emissions factors estimated from different sources.

dioxide is not included in the United States; however, some states are now passing laws to reduce CO_2 production. It is difficult to predict whether the United States will have carbon trading or a tax on carbon dioxide emissions in the first term of President Obama. The United States and China lead the world in CO_2 emissions.

In the United States, emissions from generation of electricity are primarily due to the burning of coal (Table 14.1). The average carbon dioxide emission is around 720 kg/MWh for all fuel types; of course, it is higher for coal, around 1000 kg/MWh. Thus, wind turbines and PV reduce emissions of carbon dioxide by 1 metric ton per megawatt hour when displacing coal generation; in addition, they do not require water for the generation of electricity. The production of electricity by natural gas has increased in market share, which means that carbon dioxide emissions per megawatt hour are smaller, so the average has decreased since 1990. A Minnesota group (connected with the utility industry) estimated the external costs for carbon dioxide from coal as only \$0.34 to \$3.52/ton. In Europe, carbon dioxide emission reductions are worth \$40/ton in some countries.

The numbers for emission factors (Table 14.1) were adjusted somewhat to give total values in metric tons, the same as the numbers from the Energy Information Administration. For example, the average value for sulfur dioxide from coal is 3.0 kg/MWh; however, the worst coal plant in the United States produces 18 kg/MWh. So, new coal plants have scrubbers, but nearly 40% of the coal plants do not have the same pollution control standards because they were online prior to the Clean Air Act of 1970.

14.8 TRANSMISSION

A major problem for renewable energy development, especially wind, is that many load centers are far away from the resource, and projects can be brought online much faster than new transmission lines can be constructed. For those states with electric restructuring, transmission is now by a separate company, and the questions regard jurisdiction, who pays for new lines, and if curtailment is needed because a project is producing too much power for the grid, who is curtailed, and the priority of curtailment. Even with new transmission lines, future development may be limited

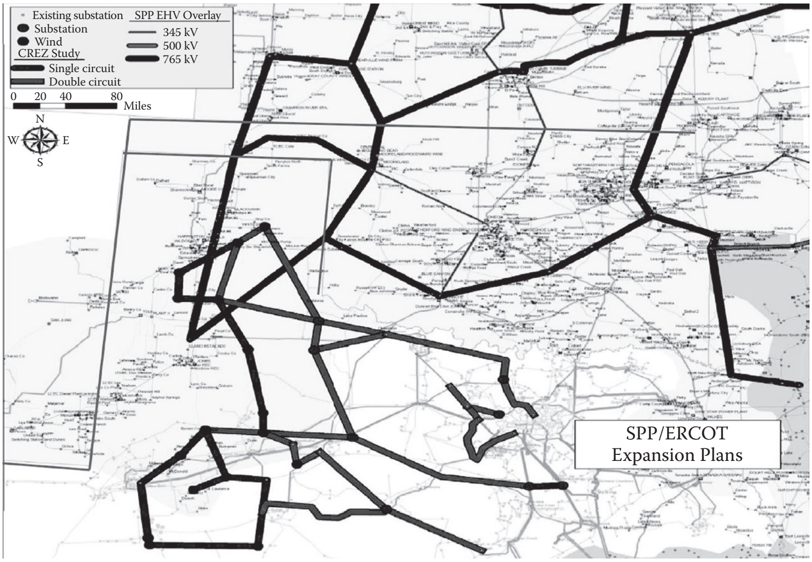

FIGURE 14.3 Transmission lines for ERCOT at planning stage for routes, construction to be completed by 2013. Transmission lines (northern set) for the Southwest Power Pool (SPP) at planning stage for some routes, others at study stage.

by transmission capacity. A large transmission investment of $12.6 billion would increase a retail bill of $70 by $1.

Texas has committed to construction of high-voltage transmission lines (345 kV), primarily to bring wind power from West Texas and the Panhandle to the load centers within the Electric Reliability Council of Texas (ERCOT). The new lines (Figure 14.3) would have a capacity of 18 GW, which means that around 11 GW of new wind capacity [17] will be added to the ERCOT system (9,000 GW when the law was passed). The Panhandle is in the Southwest Power Pool, and it is also considering new transmission lines, again primarily for wind power. Now, there is emphasis on a supernational transmission grid, similar to the interstate highway system, so planning and money are being spent on that program (see Links).

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RECOMMENDED RESOURCES

LINKS

Database of State Incentives for Renewable Energy, www.dsireusa.org. Excellent site.

DOE Energy Efficiency and Renewable Energy, www.eere.energy.gov/.

Energy Information Administration. Good site for summary of incentives, http://www.eia.doe.gov/cneaf/solar.renewables/rea_issues/windart.html.

D. Koplow, *Fueling global warming, federal subsidies to oil in the United States,* http://archive.greenpeace.org/climate/oil/fdsub.html.

National Wind Coordinating Committee, www.nationalwind.org/.

State Incentives for Renewable Energy, www.awea.org/pubs/inventory.html.

Wind Powering America, www.eren.doe.gov/windpoweringamerica/. Wind project calculator and state wind working group handbook.

NET METERING, GREEN POWER, AIR EMISSIONS, TRANSMISSION

Climate Change, http://www.epa.gov/climatechange/index.html.

EERE network. http://www.eere.energy.gov/RE/wind_economics.html.

EWEA. 2005. Large scale integration of wind energy in the European power supply; analysis, issues and recommendations. http://www.ewea.org/fileadmin/ewea_documents/documents/publications/grid/051215_Grid_report.pdf.

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Fresh Energy, http://www.fresh-energy.org/.

Green Power Markets, Net Metering Policies, http://apps3.eere.energy.gov/greenpower/markets/netmetering.shtml.

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India. http://www.uses.net/national/India/wind/.

National Electric Transmission Corridor. http://nietc.anl.gov/nationalcorridor/index.cfm.

Sustainable Development International, http://www.sustdev.org/index.php.

Trading. http://www.cleanerandgreener.org/environment/introduction.htm.

PROBLEMS

1. What type of incentives should there be for renewable energy? Give brief explanation for your choices.
2. How much support should the U.S. government provide for renewable energy? Why?
3. What type of projects should the federal government support? (Some examples are R&D, prototypes, demonstration projects, commercialization projects.) Give reasons for your answer.
4. Should state and local governments provide incentives for renewable energy? If the answer is yes, list your choices and explain why.
5. What type of education would be most effective for promoting renewable energy? At what level and to whom?
6. What are the major environmental concerns if a renewable energy system is planned for your area?
7. List two environmental concerns if a wind farm were to be located in your area.
8. At what dollar level should the federal government fund renewable energy? Fossil fuel? Nuclear energy? Compare your numbers to the federal budget for this fiscal year.
9. How many states have net energy metering of 100 kW or greater?
10. What is the longest period for net energy billing?
11. What state incentives are there for residential size systems in your state?
12. Go to http://www.dsireusa.org. How many states have renewable portfolio standards?
13. Does your utility offer green power? If yes, what are the costs?
14. Wikipedia has financial incentives for PV. Choose any country except the United States. What are the PV incentives?
15. Why is there a large amount of PV installed in Germany, Spain, and Japan?
16. How many states have rebate programs for renewable energy systems? Give range of dollar values.
17. Which states have mandates for ethanol in gasoline?

18. How many countries have mandates for solar hot water?
19. You want to install a renewable energy system for your home or residence. Choose any system and then determine if permits are needed and if so what kind you would need.
20. If you were in charge of the national energy policy for your country, what incentive would you choose to promote renewable energy? Be specific about cost and length of time.

15 Economics

15.1 INTRODUCTION

The most critical factors in determining whether it is financially worthwhile to install renewable energy systems are (1) initial cost of the installation and (2) the net annual energy production. If the renewable energy system produces electrical energy and is connected to the grid, the next important factor is the value of that energy. For large systems, it is the value of the electricity sold to the utility company; for systems using energy on site, it is generally the value of the electricity displaced, the retail value. In determining economic feasibility, renewable energy must compete with the energy available from competing technologies. Natural gas and oil prices have had large fluctuations in the past few years, and the future prices for fossil fuels are uncertain, especially when carbon emissions are included. For the United States, if the military costs for ensuring the flow of oil from the Middle East were included, that would probably add \$0.15–0.30/L (\$0.50–1.00/gal) to the cost of gasoline. To increase market penetration of renewable energy, the return from the energy generated should exceed all costs in a reasonable time. For remote locations where there is no electricity, high values for electricity from renewable energy are probably cost competitive with other sources of energy. Of course, all values for electricity produced by renewable energy systems depend on the resource, so there is a range of values.

The general uncertainty regarding future energy costs, dependence on imported oil, reduction of pollution and emissions, and to some extent availability has provided the driving force for development of renewable sources. The prediction of energy cost escalation is a hazardous endeavor as the cost of energy (COE) is driven primarily by the cost of oil. The price of oil was \$12 to \$25/barrel in the 1990s, and predictions at that time for 2003 by the U.S. Energy Information Administration (EIA) were for a gradual increase to \$30/bbl by the year 2020. However, actual values were \$99/bbl in 2007, with a peak of \$140/bbl in April 2008, and the price of oil was at \$80/bbl in June 2010, a value that is still much larger then the predicted value for 2030. In 2010, the EIA predicted that oil will be at \$108 per barrel in 2020 and \$133 per barrel in 2035. This dramatically demonstrates that oil prices have not been and will not be uniform, in terms of either time or geography. At the point in time when demand exceeds production, there will be a sharp increase in the price of oil. Some experts predicted that the peak of world oil production (http://www.oilposter.org) would be in 2007 to 2010, while others predicted it will be around 2015, and other even predicted peak oil in 2040. The EIA has a wide range of predictions for peak oil from 2021 to 2112, depending on growth in demand [1]. The most important factors are the estimated total reserves and what amount is recoverable. As price increases, it becomes economic to recover more from existing reservoirs.

As stated in the previous chapter, economics is intertwined with incentives and penalties, so actual life-cycle costs (LCCs) are hard to determine, especially when externalities of pollution and government support for research and development (R&D) for competing energy sources are not included. Incentives for large and small renewable systems have driven and will drive the world market.

15.2 FACTORS AFFECTING ECONOMICS

The following list includes most of the factors that should be considered when purchasing a renewable energy system for residence, business/commercial, farm and ranch, and industry uses:

- Load (power) and energy
- COE from competing energy sources to meet need
- Initial installed cost (purchase price, shipping, installation [foundation, utility intertie, labor, etc.], cost of land [if needed])
- Production of energy
- Types and sizes of systems
  - Warranty
  - Company (reputation, past history, number of years in business, future prospects)
- Renewable energy resource
  - Variations within a year
  - Variations from year to year
- Reliability
- Selling price of energy produced or unit worth of energy displaced and anticipated energy cost changes (escalation) of competing sources
- Operation and maintenance (O&M)
- General operation, ease of service
- Emergency services and repairs
- Major replacement cost over lifetime (e.g., batteries 5 to 7 yr)
- Insurance
- Infrastructure (are service personnel available locally?)
- Cost of money (fixed or variable interest rate)
- Inflation (estimated for future years)
- Legal fees (negotiation of contracts, titles, easements, permits)
- Depreciation if system is a business expense
- Any national or state incentives

Every effort should be made to benefit from all incentives, and the difference in incentives may determine type and size of renewable system. The cost of land is a real cost, even to those using their own land. This cost is often obscured because it occurs as unidentified lost income. Reliability, or availability, is important in determining the quantity of energy produced. For optimum return, the system must be kept in operation as much of the time as possible, consistent with safety considerations. Background information on system performance, including failures, should be sought and used to estimate the downtime. The distribution of the energy production throughout the year can affect the value of the energy. If most of the energy comes during a time of increased demand on the utility system or during the time energy is needed on the site, then that energy is clearly of more value. For example, photovoltaic (PV) systems produce energy that matches the load for air conditioning.

Renewable energy systems can produce electricity (1) for consumption on site, (2) to sell to a utility, or (3) both. The electricity used on site displaces electricity at the retail rate. If net energy billing is available, even the energy fed back to the utility is worth the retail rate, up to the point of positive feedback (dependent on period or rollover). If more energy was produced than was used during the billing period, then that energy is sold for avoided cost. The price paid by the utility is either negotiated with the utility or decided by a public regulatory agency.

Example 15.1

A wind turbine produces 2,000 kWh in a month. There are two meters; one measures energy purchased (3,000 kWh) from the utility company, and the second measures energy fed back to the grid (1,200 kWh). The energy displaced by the wind turbine is 800 kWh (2,000 − 1,200), the on-site use. The retail rate from the grid is $0.09/kWh. The value of the excess energy sold to the grid is $0.03/kWh, which is the avoided cost and in many cases is the fuel adjustment cost of the utility.

This is the billing if two meters are used:

Meter	**kWh**	**Rate, $**	**Bill, $**
One	3,000	0.09	270
Two	1,200	0.03	–36
Month charge for meter 2			15
Total			$249

In net energy billing, one meter runs forward and backward:

Meter	1,800[a]	0.09	$162

[a] 3,000–1,200 kWh

Clearly, net energy billing is preferable because all the energy produced by the renewable energy system is worth the retail rate, up to the point at which the meter reads no difference for the billing period. Notice that energy displaced, 800 kWh, is worth $72, the retail rate.

The costs of routine O&M for individuals represent the time and parts costs. Information on system reliability and durability for long time periods may be difficult to obtain, so the cost of repairs will be difficult to estimate. It is important that the owner have a clear understanding of the manufacturer's warranty, and that the manufacturer has a good reputation. Estimates should be made on costs of repairing the most probable failures. Insurance costs may be complicated by companies that are uncertain about the risks involved in a comparatively new technology. However, the risks are less than operating a car.

Inflation will have its principal impact on expenses incurred over the lifetime of the product. The costs of O&M and especially the unanticipated repairs fall into this category. On the other hand, generally with inflation cheaper dollars would be used to repay borrowed money (for fixed-rate loans).

15.3 ECONOMIC ANALYSES

Economic analyses, both simple and complicated, provide guidelines, and simple calculations should be made first. Commonly calculated quantities are (1) simple payback, (2) COE, and (3) cash flow.

A renewable energy system is economically feasible only if its overall earnings exceed its overall costs within a time period up to the lifetime of the system. The time when earnings equal cost is called the *payback time*. The relatively large initial cost means that this period could be a number of years, and in some cases, earnings would never exceed the costs. Of course, a short payback is preferred, and a payback of 5 to 7 yr is acceptable. Longer paybacks should be viewed with caution.

How do you calculate the overall earnings or value of energy? If you did not have any source of energy for lights, radio, and maybe a TV, a cost of \$0.50 to \$1.00/kWh may be acceptable for the benefits received. Many people are willing to pay more for green power because they know it produces less pollution. Finally, a few people want to be completely independent from the utility grid, no matter if the system would never meet costs when compared to COE from the utility. As noted, independence from the grid means efficient use and conservation (low energy use).

15.3.1 SIMPLE PAYBACK

A simple payback calculation can provide a preliminary judgment of economic feasibility for a renewable energy system. The difference is usually around 5–7% between borrowing money for a system and lost interest if you have enough money to pay for the system. However, in 2010, the lost interest rate was very low, so paying for the system and counting on future escalation in competing energy cost made renewable systems more economic. The easiest calculation is cost of the system divided by cost displaced per year and assuming that O&M are minimal and will be done by the owner.

$$SP = IC/(AEP * \$/\text{kWh}) \tag{15.1}$$

where SP is simple payback (years); IC is the initial cost of installation (dollars); and AEP is the annual energy production in (energy units)/year if comparing to electricity (kWh/yr), and \$/(energy unit) is the price of energy displaced; if electricity, that value is cost per kilowatt hour, the rate paid to the utility company.

Example 15.2

You purchased a 300-W solar system for electricity for lights, radio, and television.

Installed cost = \$2,000, produces 500 kWh/yr at \$0.50/kWh

\$0.50/kWh is the estimated cost for remote electricity.

$$SP = \$2{,}000/(500\ \text{kWh/yr} * 0.50\ \$/\text{kWh})$$

$$SP = 2{,}000/250 = 8\ \text{yr}$$

A more complex calculation would include the value of money, borrowed or lost interest, and annual O&M costs.

$$SP = \frac{IC}{AEP * \$/\text{kWh} - IC * FCR - AOM} \tag{15.2}$$

where \$/kWh is the price of energy displaced or the price obtained for energy generated; *FCR* is the fixed charge rate (per year); and *AOM* is the annual O&M cost (dollars/year). The FCR could be the interest paid on a loan or the value of interest received if you had not displaced money from savings. An average value for a number of years (5) will have to be assumed for cost per kilowatt hour for electricity displaced. Equation 15.2 involves several assumptions; the same number of kilowatt hours is produced each year, the value of the electricity is constant, and there is no inflation. More sophisticated analysis would include details such as escalating fuel costs of conventional electricity and depreciation. In general, these factors might reduce the payback.

Example 15.3

You purchase a 2-kW wind turbine with inverter to connect to the grid, IC = \$11,000. The unit produces 5,000 kWh/yr. You are losing interest at 4% on the installed cost, but that value is reduced as you generate electricity, so assume half. The retail rate of electricity is \$0.09/kWh.

$$SP = 11{,}000/(5{,}000 * 0.09 - 5{,}500 * 0.04) = 11{,}000/(540 - 220) = 11{,}000/320 = 34\ \text{yr}$$

You would think twice before purchasing this system on an economic basis, and no O&M was included. A cash flow would give a better idea of payback time.

15.3.2 COST OF ENERGY

The COE (value of the energy produced by the renewable energy system) gives a levelized value over the life of the system. The lifetime depends on the type of system and is assumed to be 30 yr for PV and 20 yr for wind turbines. Lifetimes for other renewable energy systems will probably fall within this range, except for large hydro, which will be much longer. The COE is primarily driven by the installed cost and the annual energy production.

$$COE = (IC * FCR + AOM)/AEP \tag{15.3}$$

where AEP is the annual energy production (net).

The COE is one measure of economic feasibility, and it is compared to the price of electricity from other sources (primarily the utility company), the price at which generated energy can be sold, or the price of energy from other sources.

Example 15.4

A renewable energy system has the following costs and production:

$$IC = \$250{,}000,\ FCR = 8\% = 0.08,\ AOM = 1\% \text{ of } IC = \$2{,}500/\text{yr}$$

$$AEP = 120{,}000 \text{ kWh/yr}$$

$$COE = (250{,}000 * 0.08 + 2{,}500)/120{,}000 = \$0.19/\text{kWh}$$

The COE should be compared with an estimated average cost of electricity from the utility over the next 10 yr.

The Electric Power Research Institute (EPRI; tag-supply method, Equation 15.4) includes the addition of levelized replacement costs (major repairs) and fuel costs [2]. The cost of fuel for most renewable energy systems is zero, so that term would not be included. However, some of the concentrating solar power (CSP) systems have backup heat from fossil fuels to provide dispatchable power, and the combustion of biomass in some cases would have a fuel cost. In Equation 15.3, the major replacement costs are included in the annual O&M costs, so that the AOM should be larger than the AOM used in Equation 15.4.

$$COE = (IC * FCR + LRC + AOM + AFC)/AEP \tag{15.4}$$

where LRC is the levelized replacement cost (dollars/year), and AFC is the annual fuel cost (dollars/year).

The COE can be calculated for cost per kilowatt hour or cost per megawatt hour, and the last term could be separate as AOM/AEP, again in terms of cost per kilowatt hour or cost per megawatt hour. It may be difficult to obtain good numbers for the LCR since repair costs are generally proprietary. One method is to use a 20-yr lifetime and estimate the LCR as IC/20. That means the major repairs are equal to the initial cost spread over the lifetime.

Example 15.5

For a 1-MW wind turbine, IC = \$2 million, $FCR = 0.07$, AEP = 3,000 MWh/yr, LRC = \$100,000/yr, AOM = \$8/MWh.

$$COE = (\$2{,}000{,}000 * 0.07 + \$100{,}000)/3{,}000 + 8 = 80 + 8 = \$88/\text{MWh}$$

The COE needs to be compared to all expected income, any incentives, accelerated depreciation, and so on.

The LRC distributes the costs for major overhauls and replacements over the life of the system. For example, for a system with batteries, they will need to be replaced every 5 to 7 or up to 10 yr. The LRC is an estimate for future replacement costs in terms of today's costs of components.

1. Year in which the replace is required n
2. Replacement cost, including parts, supplies, and labor RC
3. Present value of each year's replacement cost PV

$$PV(n) = PVF(n) * RC(n) \tag{15.5}$$

where $PVF(n)$ is the present value factor for year n and is equal to $(1 + I)^{-n}$; I is the discount rate and is equal to 0.069; and $RC(n)$ is the replacement cost in year n.

The LRC is the sum of the present values multiplied by the capital recovery factor (CRF):

$$LRC = CRF + \sum_{n=1}^{20} PV(n) \tag{15.6}$$

where CRF is equal to 0.093.

15.4 LIFE-CYCLE COSTS

An LCC analysis gives the total cost of the system, including all expenses incurred over the life of the system and salvage value, if any [3,4]. There are two reasons to do an LCC analysis: (1) to compare different power options and (2) to determine the most cost-effective system designs. The competing options to small renewable energy systems are batteries or small diesel generators. For these applications, the initial cost of the system, the infrastructure to operate and maintain the system, and the price people pay for the energy are the main concerns. However, even if small renewable systems are the only option, a LCC analysis can be helpful for comparing costs of different designs or determining whether a hybrid system would be a cost-effective option. An LCC analysis allows the designer to study the effect of using different components with different reliabilities and lifetimes. For instance, a less-expensive battery might be expected to last 4 yr, while a more expensive battery might last 7 yr. Which battery is the best buy? This type of question can be answered with an LCC analysis.

$$LCC = IC + M_{pw} + E_{pw} + R_{pw} - S_{pw} \tag{15.7}$$

where *LCC* is the life-cycle cost, *IC* is the initial cost of installation, M_{pw} is the sum of all yearly O&M costs, E_{pw} is the energy cost (sum of all yearly fuel costs), R_{pw} is the sum of all yearly replacement costs, and S_{pw} is the salvage value (net worth at the end of the final year; 20% for mechanical equipment).

Future costs must be discounted because of the time value of money, so the present worth is calculated for costs for each year. Life spans for renewable energy systems are assumed to be 20 to 40 yr; however, replacement costs for components need to be calculated. Present worth factors are given in tables or can be calculated.

LCCs are the best way of making purchasing decisions. On this basis, many renewable energy systems are economical. The financial evaluation can be done on a yearly basis to obtain cash flow, break-even point, and payback time. A cash flow analysis will be different in each situation. Cash flow for a business will be different from a residential application because of depreciation and tax implications. The payback time is easily seen if the data are graphed.

Example 15.6

For a residential application (tax credit available), *IC* = \$20,000, loan rate 6%, payment \$2500/yr, value of energy saved is \$2,500 (first years).

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Down payment	5,000										
Principal	15,000	13,400	11,704	9,906	8,001	5,981	3,839	1,570	0	0	0
Toward principal		1,600	1,696	1,798	1,906	2,020	2,141	2,270	1,570	0	0
Interest		900	804	702	594	480	359	230	94	0	0
Maintenance		500	500	500	500	500	500	500	500	500	500
Insurance, tax		115	115	115	115	115	115	115	115	115	115
Costs		3,115	3,115	3,115	3,115	3,115	3,115	3,115	2,279	615	615
$ energy saved		2,500	2,500	2,500	2,500	2,600	2,600	2,600	2,600	2,600	2,700
Tax credit	6,000										
Income	6,000	2,500	2,500	2,500	2,500	2,600	2,600	2,600	2,600	2,600	2,700
Cash flow	1,000	−615	−615	−615	−615	−515	−515	−515	321	1,985	2,085
Cumulative	1,000	385	−230	−845	−1,460	−1,975	−2,490	−3,005	−2684	−699	1,386

\$ energy saved = amount that would have been paid for electricity purchased from utility or the value of electricity generated by residential system and used on site. Income = value of electricity fed back to utility.

Notice that positive cash flow occurs in year 8 after the loan is paid off, and payback time is 10 yr. This cash flow analysis did not take into account present value of money.

There are a number of assumptions about the future in such an analysis. A more detailed analysis would include inflation and increases of costs for O&M as the equipment becomes older.

A cash flow analysis for a business with a \$0.021/kWh tax credit on electric production and depreciation of the installed costs would give a different answer. Also, all operating expenses are a business expense. The economic utilization factor is calculated from the ratio of the costs of electricity used at the site and electricity sold to the utility.

The core of the RETScreen tools consists of a standardized and integrated renewable energy project analysis software that can be used to evaluate the energy production, LCCs, and greenhouse gas emission reductions for the following renewable energy technologies: wind, small hydro, PV, passive solar heating, solar air heating, solar water heating, biomass heating, and ground-source heat pumps (http://retscreen.gc.ca/ang/menu.html).

15.5 PRESENT WORTH AND LEVELIZED COSTS

Money increases or decreases with time depending on interest rates for borrowing or saving and inflation. Many people assume that energy costs in the future will increase faster than inflation. The same mechanism of determining future value of a given amount of money can be used to move money backward in time. If each cost and benefit over the lifetime of the system were brought back to the present and then summed, the present worth can be determined.

$$PW = \frac{(\text{cost total for year } S) - (\text{financial benefit total for year } S)}{(1+d)^M} \tag{15.8}$$

where *cost total* is the negative cash flow, S is the specific year in the system lifetime, M is the years from the present to year S, and d is the discount rate.

The discount rate determines how the money increases or decreases with time. Therefore, the proper discount rate for any LCC calculation must be chosen with care. Sometimes, the cost of capital (interest paid to the bank or, alternately, lost opportunity cost) is appropriate. Possibly, the rate of return on a given investment perceived as desirable by an individual may be used as the discount rate. Adoption of unrealistically high discount rates can lead to unrealistic LCCs. The cost of capital can be calculated from

$$CC = \frac{1 + \text{loan interest rate}}{1 - \text{inflation rate}} - 1$$

If the total dollars are spread uniformly over the lifetime of the system, this operation is called *levelizing*.

$$\text{Annualized Cost} = \frac{PW\ d\ (1+d)^P}{(1+d)^P - 1} \tag{15.9}$$

where P is the number of years in the lifetime.

One further step has been utilized in assessing renewable energy systems versus other sources of energy, such as electricity. This is the calculation of the annualized COE from each alternative. The annualized cost is divided by the net annual energy production of that alternative source.

$$COE = \text{Annualized Cost}/AEP$$

It is important that annualized costs of energy calculated for renewable energy systems are compared to annualized costs of energy from the other sources. Direct comparison of the annualized COE to the current COE is not rational. Costs of energy calculated in the above manner provide a better basis for the selection of the sources of energy. This type of calculation also shows that renewable energy systems are economical today.

15.6 EXTERNALITIES

Externalities are now playing a role in integrated resource planning (IRP) as future costs for pollution, carbon dioxide, and so on are added to the LCCs. Values for externalities range from zero (past and present value assigned by many utilities) to as high as \$0.10/kWh for steam plants fired with dirty coal. Again, values are assigned by legislation and regulation (public utility commissions).

As always, there is and will be litigation by all sides as providers of energy do not want externalities included in their costs. The Lignite Energy Council petitioned the Minnesota Public Utilities Commission to reconsider its interim externality values. The council represented major producers of lignite, investor-owned utilities, rural electric cooperatives, and others. It focused the protest on values assigned to CO_2 emissions because from their standpoint there is an acknowledged lack of reliable science that CO_2 emissions are harmful to society. In Europe, different values have been assigned to CO_2 emissions, which makes renewable energy more cost competitive.

15.7 PROJECT DEVELOPMENT

The three most important considerations for development of large projects are the following:

1. Land (surface, offshore) with good-to-excellent resource
2. Contract to sell electricity produced
3. Access to transmission lines (proximity and carrying capacity)

A good source of information is RETScreen International, (http://www.retscreen.net/ang/home.php).

The RETScreen Clean Energy Project Analysis Software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies

(RETs). The software (available in multiple languages) also includes product, project, hydrology and climate databases, a detailed user manual, and a case study based college/university-level training course, including an engineering e-textbook.

National governments and trade associations will have information on project development and costs; for example, NREL has Wind Energy Finance (http://www.analysis.nrel.gov/windfinance/login.asp) and Windustry has a Wind Project Calculator, under Community Wind Toolbox, Chapter 3 (http://www.windustry.org/CommunityWindToolbox). In any case, there is the need for public involvement at an early stage for any project. However, in a competitive environment for land or rights offshore, how much information at what time period is up to the developer. Once the area is under contract, community involvement and education are highly recommended before any construction begins.

The following list provides more details on project development.

1.0 Site selection
  1.1 Evidence of significant resource
  1.2 Proximity to transmission lines (note possibility of future high-voltage lines)
  1.4 Reasonable access
  1.5 Few environmental concerns
  1.6 Receptive community
2.0 Land or surface
  2.1 Term: expected life of the project
  2.2 Rights: ingress/egress, transmission
  2.3 Compensation: percentage of revenue, per megawatt, or combination
  2.4 Assignable: financing requirement
  2.5 Indemnification
  2.6 Reclamation provision: bond to remove equipment at end of project
  2.7 Project life after resource assessment
3.0 Resource assessment
  3.1 Lease, cost/acre: 1 to 3 yr, or flat fee
  3.2 Corollary or existing data
  3.3 Install measurement systems, number needed
  3.4 Collect 10-min or hour data; minimum time period is generally 1 yr
  3.5 Report on resource
  3.6 Estimated energy output of project; may be for different manufacturers' equipment
  3.7 Data, report, and output projections to landowner if developer does not exercise option for installation of project
4.0 Environmental
  4.1 Review for endangered species
  4.2 Biological
    4.2.1 Wildlife habitat
    4.2.2 Fragmentation of habitat
    4.2.3 Required studies and reports
  4.3 Archeological studies

- 4.4 Noise, visual
- 4.5 Erosion, water quality
- 4.6 Solid and hazardous wastes
- 4.8 Construction material (gravel), water from landowner

5.0 Economic modeling
- 5.1 Output projections
- 5.2 Equipment costs
- 5.3 Installation costs
- 5.4 Communication and control
- 5.5 Taxes: sales, income, property (depreciation schedule), tax abatement (payment in lieu of taxes)
- 5.6 O&M estimates
- 5.7 Finance assumptions: tax credits, equity rate of return, incentives, debt rate and term (coverage ratios), debt/equity ratio
- 5.8 Other: insurance, legal

6.0 Interconnection studies
- 6.1 Interconnection request (electric reliability council)
- 6.2 Capacity limitation
- 6.3 Load flow analysis
- 6.4 Voltage controls
- 6.5 System protection

7.0 Permits
- 7.1 Local, state, federal, public land, private land
- 7.2 Land, marine use permit
- 7.3 Building permit

8.0 Sale of energy/power
- 8.1 Energy/power purchase agreement
  - 8.1.1 Long-term contract with utility
  - 8.1.2 Green power market
  - 8.1.3 Market (merchant), avoided cost
  - 8.1.4 Renewable energy credits
  - 8.1.5 Pollution/emission credits
- 8.2 Kilowatt hour: real or nominal levelized
- 8.3 Capacity, power
- 8.4 Term
- 8.5 Credit-worthy buyer
- 8.6 Facility sales agreement
- 8.7 Turnkey price, complete project

9.0 Financing
- 9.1 Source of equity: rate of return 15–18%
- 9.2 Source of debt
  - 9.2.1 Market rates
  - 9.2.2 Term of debt
- 9.3 Assignable documents
- 9.4 Third-party due diligence

10.0 Equipment purchase
  10.1 Power curve (output projection)
  10.2 Renewable equipment cost
  10.3 Turnkey construction cost
  10.4 Warranties: equipment and maintenance
  10.5 Construction financing
  10.6 Past history of manufacturer
  10.7 Availability of equity, down payment, delivery date
11.0 Construction
  11.1 Access: land, roads; marine, docks, transportation
  11.2 Foundations (excavation, concrete, other)
  11.3 Interconnection to utility
  11.4 Equipment assembly and installation
  11.5 Commissioning
  11.6 Environmental
    11.6.1 Continued monitoring of impact on wildlife
    11.6.2 Continued control of liquid and solid wastes
12.0 Operation and maintenance
  12.1 Fixed cost per unit per year
  12.2 Fixed price per kilowatt hour produced
  12.3 Availability warranties
  12.4 Penalties for nonperformance
  12.5 Types of costs
    12.5.1 Labor
    12.5.2 Management
    12.5.3 Insurance, taxes
    12.5.4 Maintenance equipment
    12.5.5 Parts on hand
    12.5.6 Nonrecurring costs: major repairs
    12.5.7 Roads, maintenance and access for landowner
13.0 Public information

Information for the public ranges from visitor centers at the O&M offices, kiosks, brochures with general information at the O&M office, to no public information and avoidance of the general public at the wind farm. One wind farm operator near an interstate highway removed an outdoor kiosk as too many visitors came into the office area seeking more information and disrupting the workforce at the site. So, the developer or operator need to have an idea of how much access to provide and where it is located. They especially do not want unaccompanied visitors in the operational area. Of course, public roads through a renewable energy project are accessible to the public. How is access controlled for offshore projects? Some projects have Web sites, and again the question concerns what information to display or provide. Do you provide updates on a Web page (e.g., about energy production), and how often?

15.7.1 Landowner Considerations

For some large projects, such as hydro, the land may be purchased, the nation or state might use eminent domain, or the land may be owned or controlled by the nation. In general, offshore areas are controlled by the nation; however, some distance from shore or tidal areas may be under local or state control. The considerations are as follows:

1. Lease resource assessment, 1–3 yr (2-yr extension may be requested due to financing, other problems).
   Flat rate or cost/acre per year ($1.75–2.00/acre).
   Access to land and installation of met stations.
   If option not exercised for project installation, collected data become property of landowner.
   Data have an estimated value of $20,000 to $25,000 for the first year of data and $10,000/yr thereafter.
   Also, if construction is not started, be sure that all rights revert to landowner at that point in time.
2. Project 20–30 to how many years? Option for extension at end, generally 10 yr.
   Payment quarterly or yearly.
   A. Royalty on production, 2–5%; escalation clause after which year?
   B. Per system, based on rated power, $4,000 to $6,000/MW/yr.
   C. A or B, whichever is larger for that year.
   D. If there is additional future revenue, for example, pollution credits, landowner should share in that return.
3. Land consideration.
   A. Fee/turbine during construction; $3,500 to $5,000/MW.
   B. Laydown, assembly area.
   C. Substation area, transmission lines (underground on site, overhead substation to utility).
   D. Road easement and material (value).
   E. Water.
   F. Gates and cattle guards.
   G. Hunting rights (none during construction phase). After commissioned, restrictions, workers in area, locations?.
   H. Renewable energy rights (if in windy area and close to transmission line, keep, sell, or sell with land?).
   I. Easement issues (http://www.windustry.org/opportunities/easements.htm).
   J. Insurance during construction.
   K. Bond for removal of turbines after project life or developer defaults (salvage value).

Contracts and leases will differ by region and type of surface (offshore), developer, resource, and access to transmission. The landowner should have an attorney read and advise on the proposed contract before signing the contract.

TABLE 15.1
Representative Timeline for Wind Farm Project

Site Evaluation	Permitting and Negotiation	Construction, Commission
Identify site, conduct preliminary evaluation, secure land options 5–8 months	Permit, land use, transmission Negotiate power purchase agreement, interconnect 12–36 months	Construction 6–12 months
Install anemometers, collect and analyze data 12–24+ months	Turbine purchase agreement 12–36 months	Commission 1–2 months
←	Developer (36–72 months)	→
←	Turbine supplier (12–24 months)	→

The landowner may receive one or more offers, and some landowners are forming cooperatives to deal with developers as in most cases the amount of contiguous or adjacent land will encompass multiple landowners. A developer trying to tie up land may say that, within a project, whatever the best offer is for one landowner, then all will receive that offer. For multiple land owners, for wind projects there is generally no guarantee that there will be wind turbines located on your land; however, for cooperatives, everyone may share in the revenue, depending on the agreement among the landowners.

In countries where national or state governments control the land or where it is communal land, the questions for the present occupants are how much is fair value for land removed from production and who receives payment and when (once or annual). What is the fair value to the population for relocation due to large dam projects? For offshore projects, who controls the surface, and who receives money on energy produced?

The total time from land/surface acquisition to an operating large project may take 3 to 6 yr (Table 15.1) for PV, CSP, wind, bioenergy, geothermal, and water projects. However, construction time for large dams will be much longer. The construction phase for most renewable energy projects can take from 6 months to 2 yr, and projects can be installed much faster than transmission lines can be built.

15.8 COST (VALUE) OF ENERGY, DIFFERENT SOURCES

The installed costs for renewable energy systems have decreased from the 1980s; however, the COE for most renewable energy systems increased after 2003. The increase was due primarily to the increased cost for steel, copper, and cement. Sometimes, project costs are noted in press releases, and for the generation of electricity, project information may be available from regulatory agencies, the Federal Energy Regulatory Commission (FERC) for electric plants (http://eqrdds.ferc.gov/eqr2/frame-summary-report.asp) and state public utility commissions. Renewable energy projects are included in FERC quarterly reports, which include type of plant, megawatt hours generated, income, and the rate paid to the project for energy sold. The problem is that the reporting of the name of the company has to be known.

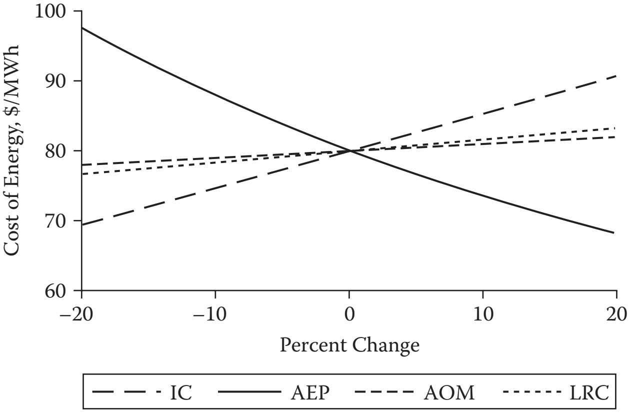

FIGURE 15.1 Sensitivity analysis for the example COE (COE = $93/MWh).

The COE can be estimated using Equation 15.4. Most COE values will be for projects installed within the past few years. Note that for large installed capacity such as hydro and wind, these are fairly good numbers. However, for prototype and a few installations, the proponents tend to have optimistic numbers for the COE, generally based on proposed utility-scale systems and not on the COE of the prototype system. A sensitivity analysis (Figure 15.1) shows how the different factors in Equation 15.4 affect the COE. The most important factor is the renewable energy production, and the second is installed cost. Note that this COE had zero fuel cost.

The COE for small systems such as solar hot water, PV, wind, and geothermal heat pumps will vary significantly due to resources, local installation costs, incentives, and value for energy displaced. The value of energy displaced in the future, fuel escalation, will vary over time, generally an increase. What value do you use: zero, general inflation, less than inflation? In general, the COE from fossil fuels will probably continue to increase at historical rates. The fuel escalation chosen for small systems will influence payback and LCCs. Cost of energy can be calculated for small systems; however, use conservative estimates for annual energy production.

Systems up to 1 kW are not cost effective when connected in parallel to the utility grid, even for single residences. Residences connected to the utility grid need 5 to 10 kW, and farms, ranches, and businesses need a minimum size of 25 kW or larger. The positive aspect of PV and solar hot water is that they are modular.

15.8.1 Passive Solar

The COE for passive solar is the most difficult to estimate since building costs vary so much by location. In general, passive solar adds around 10% to the cost of the building and can reduce heating and cooling costs by 40–80%. In most areas, there are no builders of passive solar homes, and if an architect is hired, that is an additional cost. However, in New Mexico there are a number of passive solar homes, so finding a builder is not a big problem. The best method to estimate the value of energy is to use simple payback or cash flow.

Example 15.7

A new 150-m^2 home cost is \$100/m^2. The additional cost for passive solar is \$15,000, which is added to the 6% interest loan. The value of energy saved is estimated at \$1,100/yr (10,000 kWh per year at \$0.11/kWh). The estimated payment is \$96.65/month or \$1,159/yr for a 25-yr loan, with calculation by a free loan calculator on the Web. It is easy to calculate payment for other loan periods. If the COE from an outside source increased at the rate of inflation, then the value of the passive solar increases by year, and the additional cost is paid by reduced utility costs. To improve the results, try to reduce the cost of the passive solar and have the passive solar provide more of the energy.

15.8.2 Active Solar Heat

Systems are available for industry and commercial applications; however, there are essentially few or no commercial systems for the home market. There is a market for solar hot water heaters and solar hot water for swimming pools. For a new home, the price for solar hot water is around \$15–20/month on a 30-yr loan. Installed costs for solar hot water systems for the home range from \$1,500 for do-it-yourself (DIY) systems to \$6,000 for a 3- to 4-m^2 system. The system should provide around 60–80% of the hot water needed. If you need to replace a hot water heater, you might want to check on the economics of solar hot water, especially if there are incentives.

Energy Efficiency and Renewable Energy (EERE) has a Web page for estimating the cost of solar hot water (http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=12910). The factors are system solar energy factor (SEF) and the fuel type for the auxiliary tank. Once the cost is determined, then that cost is compared to costs of a conventional hot water heater (http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=13010).

A similar procedure is used for solar hot water systems for swimming pools (http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=13280).

15.8.3 Photovoltaics

PV panels represent around 50% of the cost of the system, and prices in 2010 were around \$4/W$_P$. So, installed costs are in the range of \$7,000–10,000/kW. Of course, there are no fuel costs, and O&M costs are low. The COE for PV is around \$0.22/kWh or \$220/MWh (Figure 15.2), without incentives. PV is different in that there is not much economy of scale, so the COE for large projects is not much less than the COE for home systems.

Example 15.8

This example involves a 4-kW PV system for a home in Albuquerque, New Mexico. From the program PVWatts, the system would produce 6,700 kWh/yr. Installed costs are \$8/kW, the discount rate is 6%, the AOM is \$0.001/kWh, and the LRC is 0. Use Equation 15.4.

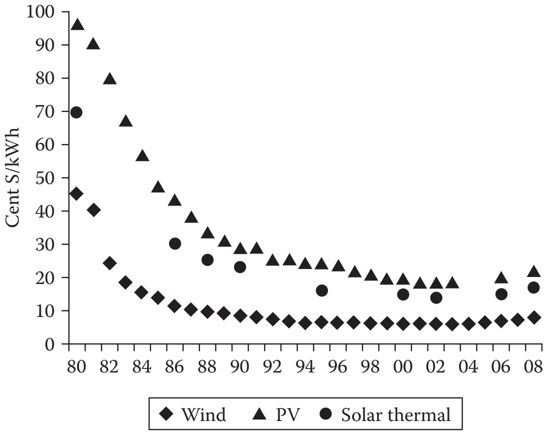

FIGURE 15.2 Cost of energy for renewable energy systems has declined dramatically since 1980. There is actually a range of values depending on resource, so plotted values are averages for large systems and locations with good-to-excellent resource.

$$COE = (24{,}000 * 0.6)/6{,}700 + 0.001 = \$0.22/\text{kWh}$$

If the 30% credit is available, then the COE = (16,800 * 0.06)/6,700 + 0.001 = $0.15/kWh.

15.8.4 CONCENTRATING SOLAR POWER

The COE for CSP is around $180/MWh (Figure 15.2), without incentives. A COE was estimated in 2008 at $150/MWh for a 100-MW parabolic trough plant with 6 h of storage in California and use of 30% investment tax credit [5]. That was based on an installed cost of $4.58 million/MW, an AOM of $6 million, and a discount rate of 6.8%. An International Energy Agency (IEA) report, *Energy Technology Perspectives, 2008*, indicates that the COE is from $125 to $225/MWh, depending on location. Future costs were predicted to be $43–62/MWh for trough plants and $35–55/MWh for tower plants, numbers that are competitive with fossil fuel for generation of electricity. If a CSP plant has auxiliary energy from fossil fuels for dispatchable power, those fuel costs have to be included.

15.8.5 WIND

The COE for wind farms is around $80/MWh (Figure 15.2), without incentives. There are economies of scale for wind, and the COE for wind farms is less than the COE for small wind systems for residences, agribusiness, and even community and distributed wind (Table 15.2). The annual energy production is estimated by the generator size method in a good wind regime, and capacity factors of 25–35% are used.

The installed costs for wind farms increased from around $1.2 million/MW in 2003 to over $2.0 million/MW in 2009 (both in 2009 dollars). The increase was due primarily to the increased cost for steel, copper, and cement and the availability of wind turbines. Therefore, the COE for most renewable energy projects also increased.

TABLE 15.2
COE for Wind Turbines in Good Wind Resource Area

Power, kW	IC, $/kW	COE, $/kWh
1–5	6,000	0.20–0.25
10	5,000	0.15–0.20
50	4,500	0.13–0.18
100	4,000	0.12–0.18
1,000	2,000	0.07–0.08

TABLE 15.3
Percentage Cost for Wind Farm Installation

Component	%
Turbine	74–82
Foundation	1–6
Electric	2–9
Connections to grid	2–9
Land	1–3
Roads, ditching	1–5
Consultants, resource assessment, other	1–3

The capital cost is the major cost for a project, and of that the wind turbine is the major component (Table 15.3). Most renewable energy projects will be similar in that equipment costs are the major item. The installed cost for offshore wind farms is around twice that of wind farms on land.

The value to the landowner can be estimated from the annual energy production or megawatts installed and the type of contract with the landowner. Examples are:

A. Royalty on production, 4–6% with escalation, generally at 10-yr periods
B. $4,000 to $6,000/MW installed per year
C. Use A or B, whichever is larger

Example 15.9

Suppose a 50-MW project has a contract to sell electricity at $35/MWh (the landowner will not receive any royalty on the production tax credit [PTC]). The income of the wind farm is

$$1.35 * 10^8 \text{ kWh/yr} * \$0.035/\text{kWh} = \$4{,}730{,}000/\text{yr}$$

Option A: Landowner would be paid $189,000/yr at 4% royalty.

Option B: Landowner would be paid $4,000 * 50 = $200,000/yr.

> At 2 acres per turbine taken out of production, then 100 acres are lost to production. Return value per acre to the landowner is then $1,890/acre/yr. This is much greater return per acre than a farmer can make from crops or livestock.

The FERC has information for electric power generation. The type of sale is shown by the rate: power purchase at fixed value, power purchase with peak and off-peak values, or if sold at market the high and low values plus the average are given. As an example, for 2008 Q1, the Wildorado Wind Ranch west of Amarillo, Texas, received $5.4 million for 178,000 MWh from a power purchase agreement at $30.77/MWh. The wind farm has an installed capacity of 161 MW, so the calculated capacity factor was 49.6% for that quarter. The capacity factor will be less for the third quarter when the winds are lower.

The National Renewable Energy Laboratory (NREL) has an online COE calculator for economic analysis of wind projects, Wind Energy Finance (http://analysis.nrel.gov/windfinance/login.asp). The output includes minimum annual energy to meet the financial criteria, levelized cost, payback period, internal rate of return, detailed cash flows, and summary. Check NREL and other sites for energy calculators for other renewable energy sources.

15.8.6 BIOENERGY

There are many different types of bioenergy systems, from those for generation of electricity from biomass, biowaste, and biogas to those for liquid fuels for transportation. In the generation of electricity from biomass, there will be fuel costs, while there may be a negative fuel cost for generation of electricity from biowaste and biogas as a result of payment for disposal of the waste. Installed cost would be for conventional boiler plants or conventional combustion engines connected to generators, with an installed cost of $1,200–2,000/kW.

For liquid fuels for transportation from bioenergy, there will be cost for the crops and transporting biomass to the conversion plant. The cost per volume for that fuel can be compared to the cost per volume for gasoline and diesel. It is important to consider the energetics of these systems; for example, the energetics are probably negative for ethanol produced from irrigated corn (well depth of 100 m). For bioenergy systems, the decommissioning costs should be covered by the scrap value.

15.8.7 GEOTHERMAL SYSTEMS

The Geysers electricity is sold for $0.03–0.035/kWh; however, for a plant built today, the cost would be $0.05–0.07/kWh. Installed costs are around $2,500/kW with an AOM of 0.01–0.03/kWh. Most geothermal power plants can run at 90% capacity factor. The value for direct use of geothermal energy is compared to the value of energy displaced from conventional sources: electricity, natural gas, oil, and coal-fired boilers.

The general rule for geothermal heat pumps is $2,500 per ton of capacity, and a typical home would use a 3- to 4-ton unit. However, the installed cost will depend on the ground source (drilled vertically or horizontal loops in ground or water). The additional cost for the geothermal aspect ranges from $4,000 to $11,000 for a 3-ton system. Again, the COE will be compared to the value of energy displaced.

15.8.8 WATER

The cost of large hydro is site specific, and most of the cost is for the structure; installed costs are $1,200–1,600/kW. The construction period is long, the same as for nuclear power plants, so the cost of capital is high, and payment of interest will start before the project is completed. However, equipment has a 25- to 50-yr life, and the structure has a 50- to 100-yr life, so the COE is low. Installed costs are $4,000–2,000 for 100-kW to 30-MW plants [6]. In China, small hydro for remote villages was the cheapest source of renewable energy, larger rated power, and easiest to increase power output; however, it is also dependent on suitable locations.

A tidal system capacity factor is 20–25%. For commercial-scale tidal energy, the COE is estimated at $0.05–0.11/kWh. For the proposed 8.6-MW Severn Barrage in the United Kingdom, the COE was estimated at $0.10/kWh. An EPRI report estimated that tidal kinetic systems would have a COE of $0.06–0.013/kWh for utility-scale systems.

Wave energy COEs are estimated at $0.06–0.08/kWh in the United Kingdom, and projected COEs are $0.06/kWh for utility-scale systems. Marine current system COEs are estimated at $0.10–0.14/kWh, again with projected values at $0.06/kWh.

Microhydro installations are generally remote or village systems, so the COEs will be higher as a minigrid would be installed. However, the cost in developing countries can be reduced by in-kind labor [7]. The installed costs ranged from $900 to $6,000 for five developing countries [8].

15.8.9 VILLAGE POWER

The economics vary widely for village power due to components from different manufacturers and difficulty of reaching remote locations. The source of energy chosen for village power depends on the renewable resource and how much storage (1 to 3 days) is needed. Wind, solar, minihydro, and maybe even geothermal systems are considered, and then LCCs are used for one or more components of the system, which may also include fossil fuels, generally diesel. LCCs will help determine the ratio of different renewable energies in a hybrid system.

The China SDDX project (2002–2005) consisted of 866 village power systems in the western provinces of China. There were 146 minihydro systems (113,765 kW) and 721 systems (15,540 kW) powered by PV, wind, or a wind/PV hybrid. The average cost was $4,370/kW, which is remarkable considering the remote locations. For the China SDDX project, minihydro was the cheapest source of energy, and for good-to-excellent wind regimes, wind was the next-lowest-cost system. Notice that the average size of the minihydro was 780 kW, compared to 22 kW for PV and wind. The advantages of PV are that there are no moving parts, and everything is at ground level.

An example of remote village power is the system at Subashi (Figure 15.3), Xinjiang Province, China. The hybrid system has wind/PV/diesel (54 kW: two 10-kW wind turbines, 4-kW PV, 30-kW diesel, 1,000 Ah battery bank, and a 38-kVA inverter). The cost was $178,000 (2003 dollars), which included the minigrid. The wind/PV produces around 150 kWh/day. To estimate the COE, you need to include fuel cost (percentage of system generation not known), major replacement cost (one

FIGURE 15.3 Hybrid system (54 kW) for village power, Subashi, Xingiang Province, China. (Courtesy of Charlie Dou.)

for sure is the battery bank every 5 to 7 yr), and O&M. Since none of these are known, only a rough estimate can be made.

$$IC = \$178{,}000,\ AEP = 75{,}000 \text{ kWh/yr (25\% generated by diesel)},$$

$$FCR = 0.04,\ LRC = \$2{,}000\text{/yr},\ AOM = \$0.01\text{/kWh, Fuel costs} = \$1.50\text{/L}$$

One liter will generate 4 kWh, so 18,750 kWh/yr uses 4,700 L; at $1.50/L this equals $7,000/yr.

$$COE = (0.04 * 178{,}000) + 2{,}000 + 7{,}000)/75{,}000 + 0.01 = 0.215 + 0.01 = \$0.23\text{/kWh}$$

If they can really generate electricity for $0.23/kWh for 20 yr, that would be very good. Remember that major problems will be O&M, replacement costs, and load growth, so village power systems need to be modular.

For example, if 20 kW is needed for a village power system, and the local resources for both wind and solar are good, do you choose wind, PV, or a hybrid system? First, try wind alone and then PV alone for the 20 kW. The capacity factor for wind is 25%, and for solar the average is 4 h/day at peak power, 80% sunshine. The estimated yearly production for a 20-kW wind turbine is 43,000 kWh, and for a 20-kW PV array, the yearly production is 23,000 kWh. Also, the installed cost for wind is cheaper than the installed cost for PV, so the wind system is the obvious choice. However, a hybrid system with a small portion of PV may be a better choice for more consistent power or a smaller battery bank. For the reasons stated, for a hybrid system the ratio of wind power to PV power would be around five to one.

Small hybrid systems (Table 15.4) are available, which usually can be purchased as modular systems. Most manufacturers do not supply prices on their Web sites, so

TABLE 15.4
Wind/PV Hybrid Systems for Producing AC Power

Company	Size, kW	Wind, kW	PV, kW	Battery, kWh	Inverter, kW	Energy, kWh/yr	$ (2009)
Bergey	10.1	7.5	2.6	84	6	12,000	78,300
Bergey	1.2	1.0	0.18	10.6	1.5	1,200	8,100
Southwest	1.3	0.4	0.88			750	

TABLE 15.5
Fuel Prices Drive the Percentage Cost for Electricity from Diesel Plants

	2004, %	2007, %
Fuel	46	77
Operation and maintenance	21	9
Major repairs, replacement	19	8
General and administration	14	6

you have to get quotes from the manufacturer or a dealer. Shipping and installation in remote locations will increase the cost; sometimes, they will double the cost of the energy components, and for overseas, import taxes will also increase the cost. From the initial cost and estimated energy production, the COE can be estimated.

15.8.10 WIND DIESEL

Wind turbines or PV added to an existing diesel generation plant are fuel savers, and the economics depend primarily on the cost of diesel fuel (Table 15.5), which depends on remote locations; of course, the economics also fluctuate with the price of oil.

At Ascension Island, four 225-kW wind turbines were connected to a grid powered by two 1,900-kW diesel generators for a low-penetration system (14–24%). Then, in 2003, two 900-kW wind turbines, controllable electric boiler, and a synchronous condenser were installed for a high-penetration system (43–64%). This saved an additional 2.4 million L of diesel fuel per year for a savings of over $3 million per year with the cost of diesel at $1.50/L. The simple payback was estimated at 7 yr, and with the increased cost of diesel fuel, simple payback became less than 5 yr.

Three 100-kW wind turbines at Toksook Bay, Alaska, produce around 675,000 kWh/yr for a wind-diesel system. The wind turbines displace 196,000 L of diesel per year, and with a cost of diesel at $1.50/L, there is a savings of $300,000/yr. If the installed cost for wind turbines is $10,000/kW, then the simple payback is 7 yr.

15.9 SUMMARY

National, state, and local entities are promoting renewable energy as a source of economic development, especially rural economic development. Proponents for

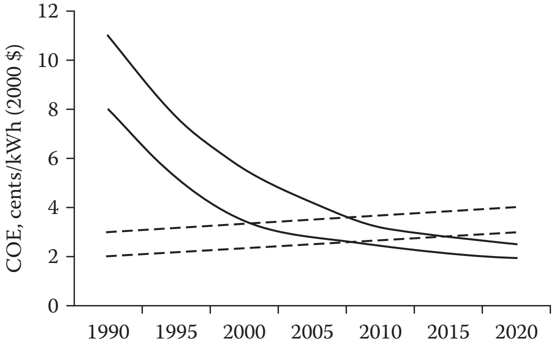

FIGURE 15.4 Range of cost of electricity (solid lines for high and low wind speed sites) from wind turbines compared to bulk power (dashed lines). (From the National Renewable Energy Laboratory.)

renewable energy systems will tout COEs that will compete with present fossil fuels and how much economic development they will bring. For example, wind projects provide 150 construction jobs (6–12 months) and 10–14 full-time jobs per 100 MW for O&M, administration, and clerical jobs. The wind farm will also pay property taxes, but in most cases, these try to obtain tax reductions for the economic development.

In 2009, there were over 6,000 MW of wind turbines installed in the corridor from Abilene, Roscoe, Big Spring, and then north from Roscoe to Sweetwater, Texas. In the middle of that is Nolan County, with over 3,000 MW of wind power; the economic impact was estimated at $360 million (14/1 multiplier) just from direct jobs [9]. Taxable property increased from $500 million in 1999 to $3 billion in 2009, and royalty payments to landowners were estimated at over $17 million in 2009.

The Colorado Green Mountain wind farm near Lamar, Colorado, started construction in the summer of 2003. The 162-MW project is located on 4,790 ha (11,840 acres) with 14 landowners. During construction, there were 200 to 300 jobs and after completion around 15 local jobs. The project owner receives an income from electricity sold of around $18 million/yr, of which the landowners receive around $800,000/yr (only 2% of land taken out of production), and the wind farm will pay around $2 million per year in property taxes. The project was purchased for $212 million by Shell and PPM from GE Wind.

Wind farms are the cheapest renewable energy source for generating electricity as COEs are $60–80/MWh, and these numbers are starting to compete with new plants powered by fossil fuels. Note that future predictions were for trends (Figure 15.4), not actual values. Of course, this graph did not predict the increase in COE after 2003 or the effect of the recession in 2008–2009. The COE numbers are for good-to-excellent wind regimes and for 30-MW and above wind farms for economy of scale on construction and O&M.

Levelized costs of energy for different sources (Figure 15.5) show wind as competitive [10] with new power plants using other sources of energy and even with combined cycle gas turbines, which produce electricity from natural gas at $5.00/mcf (1000 cubic feet). The values in the graph are averages, and there will be a

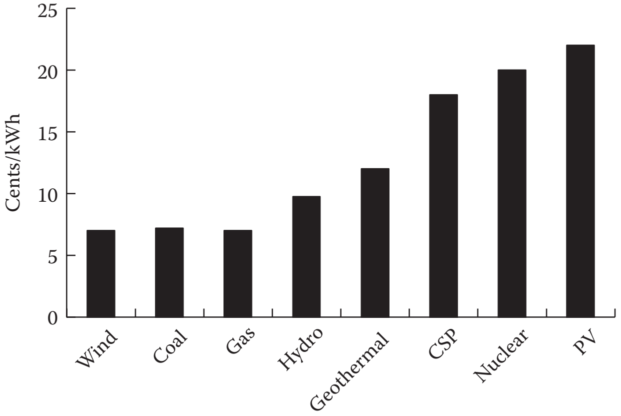

FIGURE 15.5 Estimated cost of electricity from new power plants, 2008.

range of values for each source. Another source is the work of Lazard [11] for comparing COEs for generation of electricity. Cost of energy from nuclear plants is somewhat difficult to estimate since none has been built in the United States in a number of years.

From economics, from mandates (legislation or regulation), or on a voluntary basis, there will be more use of renewable energy. Traditional energy sources have an advantage in that fuel costs are not taxed, while for renewable energy the fuel costs are free. The problem is the high initial costs for renewable energy, and most people would rather pay as they go for the fuel. Even with the increased production of small wind turbines (100 kW and smaller), in 2009 they are still not cost competitive with electricity from the grid. However, if LCCs are used, then many renewable energy systems are competitive in many situations.

Green pricing is now available in many locations, and the number is increasing. The premium is around $0.03/kWh for a block of 100 kWh/month, and in some cases that number has decreased. New England Electric Systems has a green request for proposal (RFP) under which the utility agreed to acquire 200 million kWh/yr from renewable resources. Pacific Gas & Electric estimated that up to 40% of their power could come from renewables without adding storage. Another major driving force for renewable energy is economic development and jobs at the local or state level. That is because renewable energy is local; it does not have to be shipped from another state or country.

The capacity of existing transmission lines and curtailment of wind farms is a major problem. The other major problem is that the wind and solar resources are generally quite distant from major loads, and geothermal is localized. Enhanced geothermal and geothermal heat pumps can be used over wide areas. However, new transmission lines will have to be built. The questions is; with deregulation, who will finance the construction and overcome the right-of-way problems?

The value of externalities ranges from zero (past and present value assigned by many utilities) to as high as $0.10/kWh for steam plants fired with dirty coal. Again, values are being assigned by legislation and regulation (public utility commissions). As always, there is and will be litigation by both sides on external costs and who should pay for them.

15.10 THE FUTURE

As stated, predictions about the future are risky and generally wrong on specifics, but sometimes trends are fairly clear. For example, a prediction for the price of oil at $200/bbl by 2020 is questionable; however, I am fairly confident that the price of oil will increase over the next decade. With that in mind, here are some comments on the future of renewable energy.

At some point in time, there will be a distributed renewable energy market, very similar to the farm implement business today. A farmer, rancher, or agribusiness will go to the bank and obtain a loan for a renewable energy system (size range from 25 to 500 kW). This system will expect to provide a payback of around 5 yr, and it will make money for the next 15 yr. The nice thing about dollars from renewable energy is that the COE will not fluctuate like for other agriculture commodities.

High- and extrahigh-voltage transmission lines will be built from the plains areas in the United States to load centers. The same will be done in other countries, which will install large renewable energy projects for production of electricity: European Union, China, India, and others. Income (dollars per kilowatt hour) that landowners receive as royalties for new large, renewable energy systems will decrease as installed costs decrease. Within 5–8 yr, renewable energy power will compete with fuel adjustment cost without PTCs but with carbon credits.

There will be trading in carbon dioxide in the United States, much as there is now trading in nitrogen oxide (NOX) and sulfur dioxide (SOX). At that point, renewable energy, especially wind energy, becomes the cheapest source of electricity. Renewable energy systems are being installed in the world with part of the income derived from carbon trading. It is the same as European countries buying forests in South America to reduce carbon dioxide emissions. Cooperative or community systems, from 1 to 10 units, will become common because of the economies of scale. Near Luverne, Minnesota, 66 farmers formed a limited liability corporation to purchase four 950-kW wind turbines. They raised 30% of the $3.6 million and borrowed the rest through local banks. With the PTC, they expect a 17% return on investment.

The world faces a tremendous energy problem in terms of supply and in terms of emissions from the use of fossil fuels. The first priority is conservation and energy efficiency, and the second is a shift to renewable energy for a sustainable energy future. This shift has started to occur, and the renewable energy market will grow rapidly over the next 30 yr.

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4. J. M. Sherman, M. S. Gresham, and D. L. Fergason. 1982. Wind systems life cycle cost analysis. RFP-3448, UC-60; NREL; Wind energy finance. http://www.nrel.gov/docs/fy04osti/33638.pdf.
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7. Micro-hydro power, practical action. http://practicalaction.org/energy.
8. S. Khennas and A. Barnett. 1999. Micro-hydro power: An option for socio-economic development. http://www.afghaneic.net/renewable/16%20smail.pdf.
9. Nolan County: Texas wind energy economics case study. http://www.cleanenergyfortexas.org/downloads/Nolan_County_case_study_070908.pdf.
10. Energy technology and cost performance data. http://www.nrel.gov/analysis/costs.html.
11. Lazard. June 2008. Levelized cost of energy—version 2.0. http://www.narucmeetings.org/Presentations/2008%20EMP%20Levelized%20Cost%20of%20Energy%20-%20Master%20June%202008%20(2).pdf.

RECOMMENDED RESOURCES

LINKS

Long-Term World Oil Supply

Fueling global warming subsidies for oil. http://www.greenpeace.org/~climate/oil/fdsub.html.

International Energy Outlook 2010, U.S. Energy Information Administration. http://www.eia.doe.gov/oiaf/ieo/index.html.

The Oil Age Poster. http://www.oilposter.org.

COST MODELING

P. W. Petersik. Modeling the costs of U.S. wind supply. http://www.eia.doe.gov/oiaf/issues/wind_supply.html#rwgt.

NREL, Energy Analysis, Market Analysis Models and Tools. http://www.nrel.gov/analysis/analysis_tools_market.html.

Open Energy Info. http://en.openei.org/wiki/Main_Page.

RET Finance is an Internet-based cost of electricity model that simulates a 20-year nominal dollar cash flow for a variety of renewable energy power projects. http://analysis.nrel.gov/refinance/login.asp.

U.S. FEDERAL BUDGET

Department of Energy. Thirty years of DOE Funding. http://www.cfo.doe.gov/crorg/cf30.htm.

Department of Energy. FY2011 Budget Request. http://www.energy.gov/about/budget.htm.

PROBLEMS

1. What are the two most important factors (the factors that influence COE the most) in the COE formula?
2. Calculate the simple payback for a Bergey 1-kW wind turbine. Go to http://www.bergey.com to get a price. Place the turbine on a 60-ft (18 m) tower. It produces 2,000 kWh per year. Assume O&M and FCR = 0.
3. Calculate the simple payback for solar hot water (four modules) for a swimming pool in northern Florida. Choose any manufacturer, note the type, specifications, installed cost, energy production, and value of energy displaced. You will have to calculate or estimate energy production.
4. Use the EERE Web page to estimate the cost of a solar hot water system for your home. http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=12910.
5. Calculate the COE (use Equation 15.3) for a Bergey 10-kW wind turbine (grid connected) on an 80-ft (24 m) tower for a good wind regime. You can use a simple method for estimating the annual kilowatt hours.
6. Calculate the COE (use Equation 12.4) for a 50-kW wind turbine that produces 110,000 kWh/yr. The installed cost is $200,000, the fixed charge rate is 6%, O&M are 1% of installed cost, and levelized replacement costs are $2,000/yr.
7. Explain LCCs for a renewable energy system.
8. Do an LCC analysis for a 5-kW PV system installed in Amarillo, Texas. Use tilt angle = latitude.
9. Calculate the COE for a proposed tidal system: 8 GW, 20% capacity factor, installed costs = $2,500/kW, annual O&M = $120 million, FCR = 6%.
10. The COE from a wind farm is around $0.06/kWh. Make a comparison to nuclear power plants. What is the retail rate for the latest nuclear power plants installed in the United States? (Do not calculate; find an estimate from any source.)
11. What are today's values for inflation, discount rate, interest rate? What is your estimate of fuel escalation, average/year between now and the year 2015?
12. An 80-MW wind farm (80 wind turbines, 1 MW) was installed in White Deer, Texas. The utility company is paying an estimated $0.026/kWh for the electricity produced. Estimate the yearly income from the wind farm. You could find actual income from the FERC site. If the landowners get a 4% royalty, how much money do they receive per year?
13. For wind farm in problem 12, installed costs were $1,000/kW, FCR = 9%, capacity factor (annual efficiency) = 35%, AOM = 0.01/kWh. Calculate the COE using Equation 15.4. You will need to estimate the levelized replacement costs or calculate using Equations 12.5–12.7. Compare your answer to the $0.026/kWh, which is the estimated price the utility company is paying the wind farm. How can the wind farm make money?
14. Estimate the COE for a hydrokinetic tidal system: IC = 2,500 kW, capacity factor = 25%, FCR = 8%.
15. What is the price of oil ($/bbl) today? Estimate the price for oil ($/bbl) for the years 2015 and 2020. Estimate the price for oil when the costs for

the military to keep the oil flowing from the Middle East are added. Place results in a table.

16. For a remote 2-kW microhydro system, estimate the COE. Installed cost = \$12,000 and it produces 40 kWh/day; FCR = 6%; neglect AOM.
17. Go to the FERC Web site for power plant reporting. Pick any wind farm. What were the data reported for the latest quarter, energy production, cost, cost per megawatt hour? Calculate the capacity factor for that quarter. (http://eqrdds.ferc.gov/eqr2/frame-summary-report.asp)
18. A village power system is to have 20-kW wind, 5-kW PV, a battery bank for 2 days, a 20-kW inverter. Estimate the annual energy production.
19. For problem 18, estimate an installed cost. You may use components from any manufacturer. Also, include the cost for a minigrid for 200 households, 1 clinic, 1 school, 1 government building.
20. Estimate the cost of energy for a wave system with a 50-MW plant. You may use any type or manufacturer. Be sure to note specifications, energy production, and so on.
21. Why is present worth used in estimating future costs/benefits?
22. Estimate the COE for any CSP system. Note all input data, specifications, and so on.
23. In your opinion, what do you foresee for the cost (\$/kWh) of externalities for electricity generated from coal for 2015? For 2025? You might want to write this number down and see how it compares to the actual value.

Appendix

We are using the SI (International System of Units) units: meter, kilogram, second. For those who are used to English units, it may be somewhat difficult to visualize the size of the quantity; however, SI makes deriving the units in problems much easier. Almost all of the problems will have units associated with the answers. Be sure to include the units. Also, an answer should reflect the correct number of significant digits.

A1 MATHEMATICS

EXPONENTIAL GROWTH

Values of future consumption r can be calculated from the present rate r_o and the fractional growth per year k.

$$r = r_0 e^{kt} \tag{A1.1}$$

where e is the base of the natural log, and t is the time. Note that the exponent has to have no units.

Example A1.1

Present consumption is 100 units/yr, and the growth rate is 7%. What is consumption after 100 yr?

$$r = 100e^{0.07*100)} = 100 * e^{7} = 100 * 1{,}097 = 1 \times 10^{5}$$

So, after 100 yr, the consumption is 1,000 times greater.

DOUBLING TIME

Doubling time, $T2$ in years, for any growth rate can be calculated from Equation A1.1. The final amount is $2 * r_o$, so from Equation A1.1,

$$2\ r_0 = r_0 e^{kt} \text{ or } 2 = e^{kT2}$$

Take the natural logarithm of both sides of the equation.

$$\ln 2 = kT2, \text{ which is } T2 = 0.69/k$$

or for percentage growth rate R

$$T2 = 69/R$$

In terms of consumption, remember that it is always the last doubling time that is the problem with a finite resource. The amount needed is the sum of all the previous doubling times plus 1. The total sum of the resource used from any initial time to any final time T can be estimated by summing up the consumption per year. This can be estimated using a spreadsheet, or if r is known as a function of time, then the total consumption can be found by integration. The total consumption for exponential growth is given by

$$C = \int r\,dt = \int_0^T r_0 e^{kt}\,dt = \frac{r_0}{k}\left(e^{kT} - 1\right) \tag{A1.2}$$

Lifetime of a Finite Resource

If the magnitude of the resource is known or can be estimated, then the time T_E when that resource is used up can be calculated or estimated by spreadsheet for different growth rates. The size of the resource $S = C$ is put in Equation A1.3, and the resulting equation is solved for T_E.

$$S = \frac{r_0}{k}\left(e^{kT_E} - 1\right)$$

$$T_E = \frac{1}{k}\ln\ k\frac{S}{r_0} + 1 \tag{A1.3}$$

If the demand is small enough or is reduced exponentially, a resource can essentially last forever. However, with increased growth, T_E can be calculated for different resources, and the time before the resource is used up is generally much shorter than most people would have estimated. For example, in 2008, U.S. oil consumption was $7.2 * 10^9$ bbl/yr; however, U.S. crude oil production was $1.8 * 10^9$ bbl/yr. Simple division of estimated reserves by today's production gives only 20 yr for domestic oil at today's rate of oil production. Of course the timeframe will be longer as U.S. domestic oil production has been declining (see Figure 2.6). The difference between consumption and domestic oil production may be met by conservation and efficiency (more fuel efficient vehicles; hybrid, plug-in hybrid, electric, and natural gas vehicles) increased import of oil, and biofuels.

According to the some energy companies, the continued growth in energy use in the United States is to be fueled by our largest fossil fuel resource, coal, and by nuclear energy. How long can coal last if we continue to increase production to offset decline in domestic production of oil and to reduce the need for importation of oil? The preceding analysis allows you to make order-of-magnitude estimates. Also, increased or even current production rates of fossil fuels may have major environmental effects. Global warming has become an international political issue.

The lifetime can be estimated for different finite resources (Table 2.1), and in general the time is short, especially if there is increased demand. Remember, these are only estimates of resources, and other estimates will be higher or lower depending on demand and cost (as cost becomes higher, reserves are usually increased, but there is a limit to finite resources). A good source for examining energy and exponential growth is the work of A. A. Bartlett ("Forgotten Fundamentals of the Energy Crisis," *American Journal of Physics*, 46(9), 876, 1987).

SIGNIFICANT DIGITS

Answers to problems and estimates cannot be more accurate than the information available for input. With calculators and personal computers, it is common to have eight or even more significant digits displayed; however, the answer can only have the same number of significant digits as the least-accurate data input.

Example A1.2

The mass of a body is 1.05869 kg. This has seven significant digits. This body is traveling at 1.53 m/s. This has three significant digits. The momentum of the object is mass * velocity.

Momentum =1.08569 * 1.53 = 1.6611057 kg m/s (using a calculator)

However, the answer cannot be more accurate than three significant digits, so the answer is

Momentum = 1.66 kg m/s

For decimals, leading zeros do not count; for example, 0.000152 has three significant digits. If you use powers of ten, that would be $1.52 * 10^{-4}$.

ORDER-OF-MAGNITUDE ESTIMATES

In terms of energy consumption, production, supply, and demand, estimates are needed, and an order-of-magnitude calculation will suffice. By order of magnitude, we mean an answer (one significant or at most two significant digits) to a power of ten.

Example A1.3

How many seconds in a year? With a calculator, it is easy to determine:

365 days * 24 h/day * 60 min/h * 60 s/h = 31,536,000 s

When you round to one significant digit, this becomes $3 * 10^7$ s.

For two significant digits, the answer is $3.2 * 10^7$ s.

For an order-of-magnitude estimate, round all input to one number with a power of ten, then multiply the numbers and add the powers of ten. So, without a calculator, the calculation becomes

$$4 * 10^2 * 2*0^1 * 6 * 10^1 * 6 * 10^1 = 4 * 2 * 6 * 6 * 10^5 = 288 * 10^5$$

$$= 3 * 10^2 * 10^5 = 3 * 10^7$$

A2 CONVERSION

Conversions are available on Web pages or widgets.

Length: 1 m = 3.28 ft, 1 km = 0.62 mile, 1 m = 100 cm

Mass: 1 kg = 2.2 lb, 1 metric ton = 1,000 kg = 2,205 lb, 1 ton = 2,400 lb,
1 short ton = 2,000 lb

Metric tons will be used, unless stated otherwise.

Area: 1 hectare = 10,000 m^2 = 2.47 acres, 1 km^2 = 100 hectares

Volume: 1 L = 1,000 cm^3, 1 L = 0.264 gal, 1 m^3 = 1,000 L,
1 barrel oil (bbl) = 42 gal = 159 L

Speed: 1 m/s = 2.24 mph, 1 km/h = 0.62 mph

Power: 1 kW = 1.34 horsepower

Temperature: Kelvin, K; Celsius, C; Fahrenheit, F

$$T\,(°K) = T\,(°C) + 273,\ T\,(°C) = (5/9) * [T\,(°F) - 32]$$

Freezing point of water = 0 (°C) = 273 (°K) = 32 (°F)

Boiling point of water = 100 (°C) = 373 (°K) = 212 (°F)

Energy Conversion Factors

1 calorie (cal) = 4.12 joules (J)

Kilocalorie = 1 calorie (the unit used in nutrition) = 1,000 calories

1 Btu = 1,055 J

1 therm = 10^5 Btu = 100 ft^3 of natural gas

1 quadrillion Btu (quad) = 10^{15} Btu = 1.055 EJ

1 kWh = 3.6×10^6 J = $3.4 * 10^3$ Btu

R-value conversion, 1 (h ft^2 °F/Btu) = 0.17611 (m^2 °K/W)

U values, U = 1/R

AVERAGE ENERGY CONTENT

Oil, 1 metric ton = 7.2 bbl = 42–45 GJ,

Barrel of oil equivalent (BOE): Some units for biomass are in BOE.

1 barrel of oil (42 gal) = 6.12×10^9 J = 1.7×10^3 kWh

U.S. gal gasoline = 121 MJ

U.S. gal diesel = 138 MJ

Note: Energy content/mass is fairly consistent; however, density varies, so energy/volume is different.

Coal, 1 metric ton = 2.5×10^7 Btu = 2.2×10^{10} J

1 ft^3 of natural gas = 1,000 Btu

1 U.S. gal gasoline = 121 MJ

BIOENERGY

Wood, dry, no moisture, 1 metric ton = 18–22 GJ

Wood, air dry, 20% moisture, 1 metric ton = 15 GJ

Charcoal, 1 metric ton = 30 GJ (derived from 6–12 tons wood)

Agriculture residue, 1 metric ton = 10–17 GJ

Ethanol, 1 metric ton = 7.94 bbl oil = 26.7 GJ
(notice energy content/volume is less than gasoline)

Biodiesel, 1 metric ton = 37.8 GJ

A3 RESISTANCE TO FLOW OF HEAT

Thermos jugs resist the flow of heat as they have a vacuum between two containers and silver walls so there is no electromagnetic (EM) radiation. From my personal experience, I think that China makes the best thermos jugs in the world. All water is boiled in China, and there is always a jug of hot water available since they drink a lot of green tea.

Most insulation materials trap pockets of air. Styrofoam is extruded, expanded beads of polystyrene, which are in boards from 0.5 to 10 cm thick. Aerogels have very high *R* values, although they have not reached the commercial building market. Go to the following site for more information: http://www.mkt-intl.com/aerogels/. *R* values vary widely, so what is used depends on price and *R* value per width of material, especially if there are limitations on space available.

Obtain *R* values for blankets and batts, common building materials, surfaces, and trapped air spaces from the Internet (http://coloradoenergy.org/procorner/stuff/r-values.htm) or from a manufacturer's specifications. Oak Ridge National Laboratory has a whole-wall R-value calculator: http://www.ornl.gov/sci/roofs+walls/AWT/InteractiveCalculators/rvalueinfo.htm.