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The Political Economy of Electricity

Progressive Capitalism and the Struggle to Build a Sustainable Power Sector

Mark Cooper

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THE POLITICAL ECONOMY OF ELECTRICITY

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SERIES FOREWORD

As societies around the world grapple with rising sea levels, melting glaciers, and a changing climate, competition over scarce energy reserves, growing collective energy insecurity, and massive fluctuations in the price and affordability of energy services, what could be more important than a series devoted to the analysis of the interactions among nations, societies, and energy sectors? This series explores how human beings use energy, and how their conversion of energy fuels into energy services can impact social structures and environmental systems. It aims to educate readers about complex topics such as the modern use of fossil fuels and nuclear power, climate change adaptation and mitigation, as well as emerging trends in state-of-the-art energy technology including renewable sources of electricity and shale gas. It hopes to inform public debate and policy as humanity grapples with how best to transition to newer, cleaner forms of energy supply and use over the next century.

Apart from investigating innovations in the energy sector, and illustrating the fragile balance between energy development and environmental protection, the series also meets a demand for clear, unbiased information on energy and the environment. Books emerging from the series are accessible to the educated layperson, but the depth of scholarship makes them appropriate for a range of readers, including professionals who work in the energy sector, legislators, policymakers, and students and faculty in such fields as engineering, public affairs, global studies, ecology, geography, environmental studies, business and management, and energy policy.

Books in the series take an investigative approach to global and at times local energy issues, showing how problems arise when energy policies and technological development supersede environmental priorities but also demonstrating cases where activism and sensitive policies have worked with energy developers to find solutions. The titles in the series offer global perspectives on contemporary energy sources, the associated technologies, and international policy responses, showing what has been done to develop safe, secure, affordable, and efficient forms of energy that can continue to power the world without destroying the environment or human communities.

Benjamin K. Sovacool
Series Editor

PART I

HISTORICAL CONTEXT

1

INTRODUCTION

APPROACH AND PURPOSE: THE POLITICAL ECONOMY OF PROGRESSIVE CAPITALISM IN THE 21ST CENTURY ELECTRICITY SECTOR

Political Economy

This book frames the challenge facing the energy sector as a turning point, or critical juncture, in the third industrial revolution. The size of the task is magnified by the urgent need to meet two pressing challenges: the development and decarbonization of the global economy. The need for economic development is driven by the need to expand access to energy for billions of people who do not use any modern sources of power, and billions more whose standard of living is below a level that will enable them to thrive in a 21st-century economy. Although the link between energy consumption and economic growth has weakened in the past couple of decades, it is still significant, especially for nations at low and middle levels of development. The need for decarbonization is driven by the severe damage that carbon emissions (from the burning of fossil fuels) do to the environment.

The electricity sector is the focal point of this challenge for three reasons. First, it is the single largest global source of greenhouse gases. Second, electricity is the master energy source for household and commercial/industrial power in the 21st-century economy. Third, decarbonization requires electrification of the transportation and industrial sectors in order ultimately to meet the challenge of climate change. In short, a massive increase in affordable, low-carbon electricity production is necessary to meet the twin challenges of development and decarbonization.

At a general level, industrialization, which has been synonymous with economic development, requires a source of energy that drives the economy. Fossil fuels were the dominant source of power in the second

Industrial Revolution, and must be replaced by a new source of power to drive the third. The digital revolution—constituted by information, communications, and advanced control technologies (ICT)—is evolving to define the political economy of the 21st century, and it is largely driven by electricity.

The book, however, is not an essay in technological determinism; it is a work of political economy. In order for a technological revolution to successfully define a new era, it must define a coherent political economy embedded in a socioinstitutional structure that reflects and supports its economic functioning. Indeed, it can be argued that the political (socioinstitutional) foundation comes prior to, and sets the stage for, the successful technoeconomic paradigm in the first place. At a minimum, the two pillars on which a successful political economy is built are intricately intertwined.

The political economy of the third industrial-technological revolution, like the first two, is described in this book as a progressive capitalist revolution. The adjectives are descriptive, not normative. Capitalism is and has been the engine that produced the technologies that drive the economy and make development possible. Progressive policy is the political glue that makes the technology possible, distributes its fruits widely, and sets the political economy on a stable path.

The book, however, is also not an essay in political determinism. The outcome of the process of institutionalization is always in doubt. Critical junctures or turning points are conflict-ridden moments, where the indeterminacy is most evident. At this moment, a fierce battle is ongoing between interests grounded in incumbent technologies that dominated the old political economy (centered on fossil-fuel-powered central station facilities in the electricity sector) and an emerging political economy based on renewable/distributed and demand-side technologies. An intense debate is taking place about alternative political and economic models.

We treat political models and economic theories equally, which gives the term "political economy" its traditional positive sense. Political economy has made a strong comeback as a framework for economic analysis in recent years. We say "comeback" because, by some accounts, political economy was the traditional approach to economic analysis at the beginning of the science.

Thus, we use the term "political economy" in three ways.

A political economy is a constellation of political and economic institutions forming a coherent system that produces the material conditions in which people live. I prefer "political economy" to "mode of production" (Marx) or "mode of subsistence" (Smith) because it reminds us there are two spheres of paramount importance—political and economic. A functioning and compatible polity and economy are necessary to create a successful system. The term "political economy" also reminds us that the political is not only of equal importance, but in some senses is more important.

Political economy is also a scientific discipline with deep routine in social analysis. As Pearce puts it:

> Until recent times the common name for the study of the economic process. The term has connotations of the interrelationship between the practical aspects of political action and the pure theory of economics. It is sometimes argued that classical political economy was concerned more with this aspect of the economy and that modern economists have tended to be more restricted in the range of their studies.[1]

Flowing from the second connotation of the term, **political economy is also a pragmatic approach to action**. There is no separation between analytical and political practice. Thus, Piketty urges social scientists to engage in the "old-fashioned" practice of political economy. He argues that economics is set apart from the other social sciences "by its political, normative and pragmatic purpose. . . . The question it asks is: What public policies and institutions bring us closer to the ideal society?"[2] We hope that our analysis is "objective" in the sense that it correctly depicts reality, but there is no escaping the fact that subjectivity is inherent in all thought, nor should there be any effort made to hide the fact that we seek to influence the structure and function of the political economy through analysis and action.

The core change fueling the comeback of political economy is the rejection of the neoclassical assumption that the economy can be studied and modeled as a system devoid of political action and unaffected by policy choices. Once "market fundamentalism"[3] is overthrown and the role of policy is recognized as central to economic progress, questions of governance take center stage. How are policy choices made? By whom, and to whose advantage? Political and social institutions are now seen as key determinants of the nature, structure, and performance of the economy. While globalization has increased the importance of multinational and transnational governance, and democratization has raised the prominence of direct local and regional involvement of civil society in policymaking, the state remains the central policy institution.

The Paris Agreement

We view the Paris Agreement under the United Nations Framework Convention on Climate Change as a multistakeholder governance model for a global commons implementing principles of a progressive capitalist economic model. We argue that this is the correct approach because it recognizes the fundamental challenge of climate change as a dilemma that must balance development and decarbonization. It also recognizes the reality of the global structure of political authority in which policy must be implemented by states.

- When the treaty underlying the Paris Agreement was negotiated in the early 1990s, it was impossible to pass through the horns of the dilemma, but a technological revolution driven by progressive capitalism in the subsequent quarter century has made it possible to do so. The Paris Agreement is fully aware that the solution resides in the application and continuous expansion of the technological revolution.
- As a result of the technological revolution, the tension between economic and environmental concerns has been reduced and can be managed. The selection of economically and environmentally superior resources for the decarbonization portfolio go hand in hand.
- Given the current and likely continuing development of the technological revolution, the resources base is more than adequate to meet the need.

The primary challenge is now to build the physical and institutional infrastructure that will support a greatly expanded electricity sector that uses only renewable and distributed resources. To do so, policy must overcome three sources of resistance.

- The central station paradigm must be uprooted. Above all, nuclear power—pushed by a large and powerful constituency—is not the solution. It cannot even be part of the solution due to its fundamental conflict with the institutional framework needed by renewable/distributed/demand-based alternatives.
- Progressive principles applied in the key policies are needed—particularly the development of "command but not control" performance standards that are aggressive, long-term, procompetitive, and technology neutral. These have been successful in the past and are likely to be so in the future.
- A decision-making approach that uses a formal portfolio analysis provides transparency, precision, and legitimacy to resource selection. It is the "common sense" approach to decision making in a complex, interconnected, and uncertain environment.

This view of the Paris Agreement as a response to climate change frames it as a pattern that has been repeated several times in the quarter millennium of capitalist industrial revolution. A new technology, nurtured by the state with early support and market creation policies, is now moving to dominance and in need of discipline to control its more destructive tendencies. It has produced the tools to sustain development and overcome the problems it has created, but a socioinstitutional paradigm must be created to guide it.

OUTLINE

The book is overwhelmingly empirical. Interludes of conceptual discussion are framed in terms of concepts that are directly and immediately relevant to empirical issues. Each of the chapters is built upon an intensive review of the relevant literatures and case studies. For the chapters where resource costs, environmental impacts, and other important characteristics of resources are examined, the literature review is woven into the estimates of costs and other factors being analyzed. For each of the conceptual and qualitative chapters, separate appendices that discuss the support for the conceptualization and conclusions from the academic literature are provided.

Part I

The remainder of Part I lays out the challenge of climate change. **Chapter 2** establishes the empirical context for the analysis by describing the dilemma of continuing economic development while decarbonizing the economy. It describes three aspects of the political economy of the 21st-century electricity system. First, it uses the Paris Agreement on Climate Change to set the context of the analysis, portraying it as a product of the contemporary political economy in the positive sense of the term, which embraces technological progress and the progressive capitalist structure. Second, it shows how the technological revolution made the agreement possible. Third, it introduces “deep decarbonization” analyses that argue the task can be accomplished at costs that will not undermine prospects for continued economic development.

Chapter 2 then presents a basic quantitative analysis of the dilemma created by the need to improve the standard of living for the majority of the global population while decarbonizing the global economy. Starting with the remarkable progress in material conditions during the capitalist industrial revolution of the past quarter millennium, the analysis describes the two horns of the current dilemma in quantitative terms. The analysis shows that reducing growth in electricity consumption in the nations above the target level of consumption cannot offset the need for increased production of electricity in developing nations. In order to accommodate the needs of developing nations for growth and the desire of advanced nations to preserve their level of development, the technological revolution must continue to advance and spread.

Part II

Part II consists of two chapters that present the analytic framework, each concluding with a brief application of the broad framework to the contemporary political economy of electricity. **Chapter 3** presents a general theoretical framework for analyzing technological revolutions. This perspective is necessary because a series of industrial revolutions has created the current situation in the electricity sector. These revolutions create crises that further technological progress has solved. We show that the spread of another technological revolution will be necessary to create a path forward that allows global electricity consumption to double or triple, meeting the need for development while simultaneously slashing greenhouse gas emissions by more than nine-tenths. The chapter adopts an approach to the analysis of progressive capitalist markets that relies on well-known frameworks at two levels. At a broad macrolevel, these theories propose institutional explanations for the political economy of successful capitalist systems and argue that a turn toward progressive capitalism is needed at this critical juncture. At a meso-level, the paper adopts the structure, conduct, performance paradigm for evaluating the performance of markets, which guides the analysis in Part IV of the book.

Chapter 4 describes the innovation system at the heart of the continuously evolving progressive capitalist political economy. There are two primary thrusts to the analysis. First, it reviews the innovation-diffusion literature as an example of the critique of the neoclassical/*laissez faire* market fundamentalist model. Second, it identifies the processes that create the dynamic innovation engine of progressive capitalism and the policies that fuel that engine. We argue that the third industrial revolution is at a turning point, but it has already produced the tools for solving the problem, just as the previous industrial revolutions did. The chapter ends with a brief description of the intricate relationship between the market and the state in the development and deployment of the two most important 21st century electricity resources—solar and wind.

Part III

Part III examines the complexity of resource selection in a low-carbon electricity sector. **Chapter 5** reviews contemporary estimates of the economic costs of low-carbon resources. While the chapter relies on the most frequent traditional measures of cost, the analysis emphasizes two underappreciated aspects of these cost measures. First, faced with the long-term challenges of decarbonization, development, and transformation of the system, cost trends are extremely important. Second, while energy efficiency has always been an important demand-side option for consideration in resource acquisition, it has not been on equal footing with supply-side options.

While the economic costs of resources are the starting point and a crucial pillar on which resource acquisition must stand, they are far from the only consideration. Chapter 5 points out that many systemic and environmental factors beyond "simple" economic costs have long been included in the resource acquisition decision. Analyses of low-carbon resources with respect to these "other" factors are examined and compared to the results of the "simple" economic cost analysis. Both strongly support the renewable/distributive/demand-based approach as the key resources on which to build a least-cost, low-carbon 21st-century electricity system.

Since sufficient electricity supply is a prime objective, **Chapter 6** examines the prospects for meeting the need for low-carbon electricity with both supply- and demand-side resources, including a significant "new" type of resource that results from intelligent integration of demand and distributed energy. Resource potential is not fixed; it is a function of the technology available. Dramatic technological innovation and cost-reduction have greatly expanded the resource base for the distributed model. Reliance on new resources requires the electricity system to be organized according to an entirely different set of operational and institutional principles, which are described in Chapter 6. The fossil fuel-based approach to electricity generation in the 20th century relied on a combination of huge, inflexible baseload generators and peak load generation that could be brought on line quickly at very high operating costs. A massive physical and institutional infrastructure was created to support it. If alternatives are to replace fossil fuels, the physical and institutional infrastructure must be transformed to reflect and support the economic characteristics of renewable resources. This entails the use of communications and control technologies to integrate variable renewable generation with closely managed demand. Thus, building the necessary physical and institutional infrastructure is at least as important to the successful transformation of the electricity sector as identifying the least-cost resources.

Part IV

Part IV describes the challenges facing the new political economy. It begins in **Chapter 7** with a review of the theoretical and empirical discussions of market imperfections and failures found in the "efficiency gap" and climate change literatures. The conceptual frameworks have been offered in both literatures to explain why a purely free market, *laissez faire* market fundamentalist approach will not work. The efficiency gap literature is pivotal for two reasons. First, it has a long and rich history of market failure analysis that provides a roadmap to the areas where the active state policy discussed in Chapter 5 is needed. Second, efficiency is a key resource to ensure the adequacy of supply in a low-carbon future. These findings have even greater relevance in developing economies, where 1) the vast majority of energy growth will come in the 21st century; 2) there is great skepticism of the *laissez faire* approach; and 3) policy interventions must be crafted to reflect the fact that different nations exhibit different market imperfections. Chapter 7 also demonstrates that the climate change literature has quickly discovered what the efficiency gap literature has known for decades. It recognizes a host of market barriers and imperfections that must be overcome to speed the transition to a low-carbon environment and lower its cost.

Chapter 7 briefly reviews the empirical evidence that supports the conceptual frameworks. The review highlights the problem of inertia—and the need to break the hold of "carbon lock-in"—with policies to promote market success and facilitate innovation and deployment of new technologies. Citing over 200 empirical studies conducted in the past decade, it defines six broad categories and three dozen specific types of market imperfections that have retarded economically beneficial investment in efficiency-enhancing technologies, resulting in poor market performance. The literature review shows that these market imperfections are likely to retard investment in technologies that respond to climate change. The role of the state, described in Part II, is to implement policies to reduce the impact of these market imperfections, which will have the effect of speeding the transition to a low-carbon sector and lowering the ultimate cost.

The transition to a new political economy not only must overcome market imperfection and the inertia of the incumbent system, it must also overcome the resistance of the political and economic interests that are grounded in the existing structure. Dominant incumbent interests naturally resist such a transformation. Their assets and skill sets do not fit well within the new model. They would be significantly devalued if the alternative model were to become dominant. **Chapter 8** examines the war that incumbents have waged against the future to defend their interests.

The analysis of technological revolutions in Chapter 3 teaches that the turning point, or critical juncture, creates an intense conflict with the incumbents. Because of the fundamentally different nature of the political economy in which the two alternative systems would thrive, an "all of the above strategy" is not viable.

With massive facilities that "must run" continuously, nuclear power is the epitome of the 20th century baseload, central station model. With a low-carbon label, nuclear power has taken the mantle of the 21st-century champion of the baseload model and become the primary, central-station protagonist. However, throughout its history, nuclear power has been afflicted by very high costs, extremely long construction periods, and environmental impacts. Given the long construction period and the urgency of climate change, nuclear power's claim of carbon reduction is clouded. Nuclear advocates seek to overcome these severe disadvantages by using political power to increase subsidies and slow institutional changes that support the renewable/distributed/demand alternative.

Part V

Part V examines the urgent need for key policies to guide the emerging political economy. The ultimate purpose of the analysis is to build an intellectual platform for adopting strong progressive policies by demonstrating the convergence and consensus between the efficiency and climate change literatures, which 1) provide strong support for policy intervention; and 2) identify the attributes that ensure effective, efficient policies.

Chapter 9 describes the welfare economics of progressive policies, arguing that the interaction between significant market imperfections and large externalities creates an urgent need to adopt aggressive policies to target and speed innovation, and to transform the institutional structure of the electricity market. The chapter looks at three policies that receive a great deal of attention in the literature: putting a price on carbon, direct subsidies, and performance standards. It explains why putting a price on carbon is an inferior approach compared to implementing targeted policies to induce and speed technological change, such as subsidies, performance standards, and rate structures. The analysis makes it clear that, while putting a price on carbon has a role to play, policies that directly promote low-carbon alternatives and institutional reform should take precedence. Chapter 9 concludes by outlining principles to guide progressive policy.

Chapter 10 examines the challenge of decision making in the increasingly complex environment facing those responsible for resources selection. The chapter argues that, regardless of whether the policy is aimed at guiding capitalist markets or noncapitalist cooperatives, tools will be needed to ensure effective choices are made. In a sense, the cooperative approach needs more analytic tools because it gives up the decision-making power of the market. The chapter argues that one of the key elements of the new institutional framework is multicriteria portfolio analysis, which enables those responsible for the acquisition of resources to balance the diverse factors that must be considered in a transparent, rational, and coherent manner. We show that decision makers in fields as diverse as financial portfolio analysis, project management, technology risk assessment, Black Swan Theory, military strategy, and space exploration have developed remarkably similar analytic tools and principles for navigating their complex, ambiguous environments. Widespread adoption of this approach in society suggests that decision makers in the electricity sector can have confidence that this is a prudent approach.

In **Chapter 11,** we apply the approach outlined in Chapter 10 to the data used throughout the book. We show that the conclusion reached on the basis of traditional analysis of cost, financial parameters, and environmental characteristics is reinforced when the data is viewed through the lens of multicriteria portfolio analysis. We also show that the results are similar to qualitative efforts to engage in "risk aware" analysis. The benefit of applying the more formal multicriteria approach is to organize the many factors into a systematic approach that is more transparent, rigorous, and persuasive.

The **Epilogue** uses the political economy approach to assess the prospects for and impact of individual states in the United States supporting the Paris Agreement, if the U.S. federal government decides to withdrawal from the treaty.

2

THE POLITICAL ECONOMY OF THE PARIS AGREEMENT, TECHNOLOGICAL PROGRESS, AND THE DECARBONIZATION-DEVELOPMENT DILEMMA

INTRODUCTION

Chapter 2 presents a brief discussion of the political economy of the Paris Agreement to underscore the profound relevance of the technoeconomic basis of the response to the challenge of climate change. This analysis begins with a discussion of the Paris Agreement because it sets the context for the economic analysis. Policy choices are the essence of political economy, and in this case, their impact is indisputable. The political commitment to decarbonization is intended to be—and, if pursued, will certainly be—the dominant driver for energy resource selection and development. It is also critically important to recognize the technoeconomic reality that underlies, and is expressed in, the Agreement.

In this chapter, we argue that the technoeconomic revolution had a profound impact on the Paris Agreement, extending beyond the simple question of cost. The impact was existential. Without that technological revolution, it would not have been possible to reconcile the two great challenges of the 21st century: the aspiration of billions of people for economic development and the need to eliminate carbon emissions from the global economy.

For political reasons, the Paris Agreement hammered out in December 2015 was carefully framed as enhanced action under the existing United Nations Framework Convention on Climate Change (UNFCC) negotiated nearly 25 years earlier. We argue that the ability to arrive at the recent Agreement—adopted by a conference of almost 200 nations and signed by over half in less than a year—was the result of the technological revolution that had taken place in the intervening quarter century.

The technoeconomic context also had a profound impact on the political structure created by the Agreement to guide the response to climate change. The governance structure defined the challenge as a commons problem. It recognized the array of technology choices and the vast difference in energy resource endowments and levels of development between nations. It also recognized the need to respect the autonomy of nations.[1] The governance solution had to be geographically polycentric and vertically coherent, affording flexibility to the Parties. This required collaborative solutions and reciprocity around shared goals. As with any multistakeholder approach that relies on the principle of subsidiarity and delegates' responsibility, the success of the Paris Agreement will be determined by the ability to build trust, the development of social norms through reciprocity, the transparency of a vigorous information/evaluation framework, and light-touch sanctions (or incentives) for inappropriate or inadequate actions.

THE REVOLUTIONARY TECHNOLOGICAL UNDERPINNING

As shown in the upper graph of Figure 2.1, when the United Nations Framework Convention on Climate Change was negotiated in 1991, prospects for building a low-carbon electricity sector—and therefore a low-carbon economy—were bleak. This is captured by the comparison of the cost of the low-carbon resources generally available at the time (nuclear and onshore wind) and the cost of the dominant resource at the time (coal-fired generation, which is presented as the equivalent of overnight costs). Nuclear and wind were much more costly than the fossil fuels that drove the economy, and were not exhibiting declining cost trends.[2]

As shown in the lower graph of Figure 2.1, economic fundamentals of the supply-side options changed over the next two decades. A technological revolution in generation dramatically lowered the cost of some low-carbon technologies. It was built on a combination of public policies and support for research and development that set the direction of socially responsible economic growth and created markets.[3] Policies went well beyond basic research to support deployment and market formation, as shown in Chapter 4. The private sector responded with investment in innovation. Clean energy patents proliferated, followed by rapid deployment as costs fell.[4]

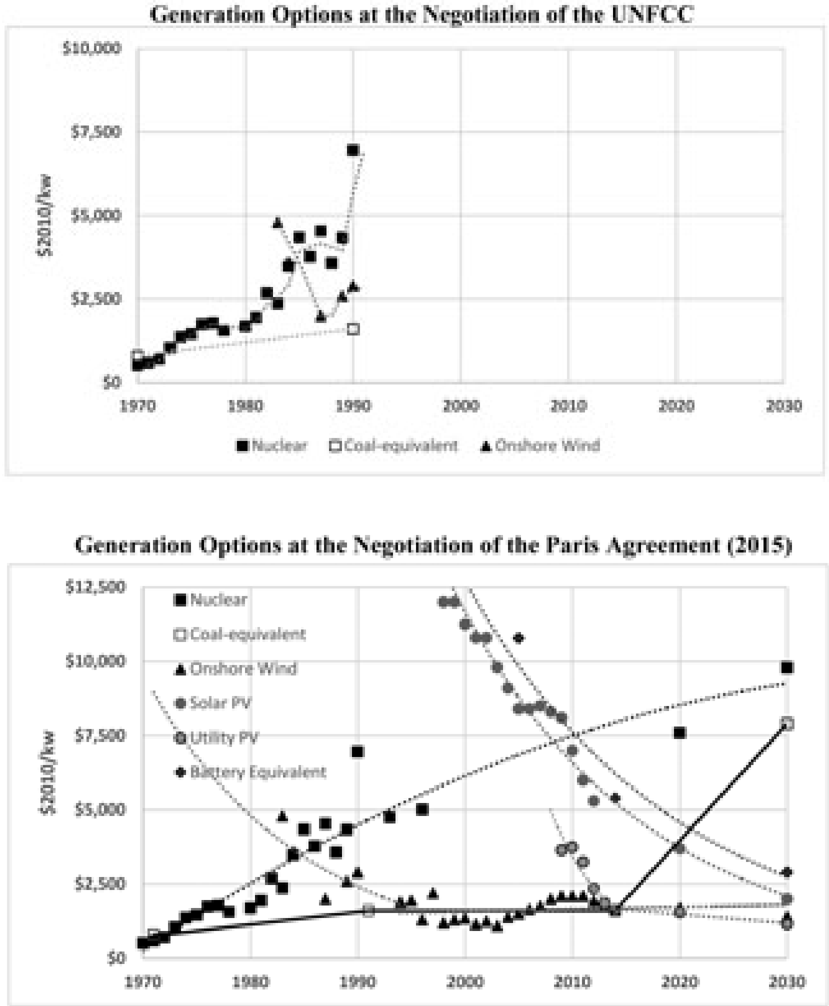


Figure 2.1 Prospects for Decarbonization under the United Nations Framework Convention on Climate Change (UNFCC)

Sources: Mark Cooper, "Nuclear Safety and Nuclear Economics, Fukushima Reignites the Never-ending Debate: Is Nuclear Power Not Worth the Risk at Any Price?" Symposium on the Future of Nuclear Power, University of Pittsburgh, March 27–28, 2012; "Small Modular Reactors and the Future of Nuclear Power in the United States," *Energy Research & Social Science* 3 (2014); Charles Komanoff, *Power Plant Cost Escalation, Nuclear and Coal Capital Costs, Regulation and Economics* (New York: Van Nostrand Reinhold, 1982); James McNerney, J. Doyne Farmer, and Jessika E. Trancik, "Historical Costs of Coal-Fired Electricity and Implications for the Future," *Energy Policy* 39 (2011); Lazard, *Lazard's Levelized Cost of Energy Analysis 9.0*, November 2015; Galen Barbose, Naïm Darghouth, Samantha Weaver, and Ryan Wiser, *Tracking the Sun VI: An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2012* (Lawrence Berkeley National Laboratory, July 2013).

While the cost of nuclear power continued to rise, the cost of wind and other low-carbon alternatives plummeted. The current cost of coal, expressed as an overnight cost equivalent in Figure 2.1, reflects changes in fuel prices and new technologies to deal with noncarbon pollutants (i.e., the long-term price for coal includes the cost of carbon capture and storage). The long-term cost of natural gas generation with carbon capture storage is generally slightly below that of coal with carbon capture and storage, but still well above the renewable/distributed resources.

As shown in Figure 2.1 and discussed in Chapter 5, another technology that has exhibited sharply declining costs—a trend that is expected to continue—is storage. The central station approach used expensive, dirty, fossil-fueled peakers to meet demand surges on a daily basis. Since the raw materials were inexpensive and the externalities of pollution were ignored, it did not make economic sense to invest in storage technologies. Today storage receives a great deal of attention.

In the 21st century environment, analysts project rapid early cost reductions, in the period from 2015 to 2030—the time period that is so crucial in the response to climate change—then a flattening of the cost curve. In the 2025–2030 time frame—and perhaps sooner—battery power will be the least-cost source of peaking power.[5] Battery power can interact dynamically with renewables to increase their load factor and/or make their output more attractive to grid operators. In fact, some argue that when all of their potential values to the operation of the grid are taken into account, batteries are beneficial at today's costs and will be very attractive at future costs. In any case, storage represents a potential resource that could reduce the cost of the 100 percent renewable scenario and make it easier/less costly to ensure its viability.

The potential for storage to transform the electricity system goes hand in hand with another technological revolution that is taking place, powered by information, communications, and advanced control technologies (ICT). It is transforming the ability to manage a dynamic electricity system that integrates decentralized, variable clean renewable supply with demand. It also brings supply into closer coordination with demand, so the size of the system needed to meet demand can be substantially reduced as a result.[6] The ICT revolution is already playing this role in the electricity system, and it could play a large role in meeting the need for low-carbon electricity at affordable costs. As discussed in Chapter 6, its contribution to the system could be substantial.

A final technological revolution is also taking place on the demand side. At the time of the 1991 negotiations, the link between economic growth and energy consumption was strong, as it had been throughout the history of the Industrial Revolution. Since then, new, more energy-efficient technologies in capital equipment and consumer durables first weakened, then severed the tie between energy consumption and economic growth. In Table 2.1, we use the United States to make this point, since it is the largest energy consumer among developed nations in both the absolute level of electricity consumed and per dollar of GDP.

ROADMAPS TO A LOW-CARBON ECONOMY

Against this background, we should not be surprised to find that several major studies were released in the run-up to the Paris Conference,[7] each with strong, positive messages for the economics of dealing with climate change:

- Three "roadmap" studies focused on decarbonizing the global economy. All define a future that is both low carbon and supports economic development at historical rates. Two of these exclude all fossil fuels and nuclear power and rely solely on renewable/distributed resources for 139 countries[8] and Greenpeace.[9]
- The third study, conducted by the Deep Decarbonization Pathways Project[10] in a series of country-specific studies, allows the use of nuclear power and fossil fuels with carbon capture and storage.
- Two independent cost projections of various energy technologies were also released: Lazard's annual *Levelized Cost of Energy Analysis*[11] and the *Australian Power Generation Technology Report*.[12] Both found that the costs of low-carbon, low-pollution resources continue to fall dramatically.

The growing stream of studies depicting a low-carbon and low-pollution future is an important part of the context for policy-making in response to the challenge of building a 21st-century electricity system.

Table 2.1 Change in U.S. Electricity Generation (kWh) per Dollar of GDP (real)

Period	Annual % Change Electricity	GDP/capita	Electricity/GDP/capita
1950–1980	+6.4	+3.5	+2.89
1980–1995	+1.9	+2.2	−0.000
1995–2015	+0.1	+1.6	−0.012

Sources: U.S. Energy Information Administration, *Monthly Energy Review, December 2015*, http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_5.pdf; "US Real GDP by Year," *multipl .com*, 2016, http://www.multpl.com/us-gdp-inflation-adjusted/table.

Analyzing the technological possibilities and economic costs of generating electricity in a low-carbon environment is the logical and critical first step toward a low-carbon economy. The electricity sector is not only the largest source of greenhouse gases, but also the best path to economy-wide decarbonization through the electrification of the transportation and industrial sectors. There will certainly be challenges in the electrification of the broader economy that merit careful consideration, analysis, and policy, but the transformation and expansion of the electricity sector is the key launch pad for the response to climate change. If that effort falters, the chances of successfully dealing with climate change will be dramatically reduced, if not eliminated.

All of the roadmap studies project a sustainable path to a low-carbon future.[13] Using long-term price projections,[14] all three studies conclude that, as a result of the technological revolution in the electricity sector, the economy (driven by the electricity sector) can be decarbonized with at most a very modest increase in the cost of energy services. All three studies envision continued, sustainable economic development while delivering significant environmental and public health benefits.

While we will not dissect the complex technological and infrastructural assumptions and mechanics of the roadmap studies, a brief review of their key elements is necessary to locate the focal point of our analysis.

Commonalities in the Roadmap Studies

The analysis of the response to climate change has moved well beyond the simple proposition of decarbonizing the electricity sector. The roadmap studies involve not only the transformation of the electricity resource mix, but they also model the elimination of fossil fuel use in the transportation and industrial sectors. While a dramatic increase in the reliance on renewable/distributed resources is a striking feature of all of the studies, the total transformation of all three sectors—electricity, transportation, and industry—is even more striking.

In taking on these very broad goals of total transformation, these studies are forced to construct a portfolio of electricity resources that is huge compared to the current portfolio of electricity resources. Total electricity generation increases dramatically because fossil fuels are backed out of the transportation and industrial sectors by the use of electricity. Renewable/distributed resources must expand to meet those needs because of the carbon constraint. For example, in the Jacobson et al. roadmap, the current levels of low-carbon/low-pollution electricity resources are less than 4 percent of the total resources that would be needed for a 100 percent transformation by 2050.[15] In the Deep Decarbonization in Australia analysis, current deployment of the technologies that make up the final portfolio equals less than 1 percent of the total needed to be deployed in 2050.[16]

Needless to say, such a transformation involves a huge amount of investment in new electricity-generation technologies, and in the transformation of the capital equipment that consumes energy. All of the studies devote a great deal of attention to demonstrating the feasibility of achieving the goal of total transformation in terms of the availability of the resource base, complementary assets (e.g., land, capital equipment), magnitude of the total investment necessary, macroeconomic impacts, and so on.

The three studies on the transformation of the economy focus on the electricity sector. They estimate the cost of generation independent from the cost of electricity-consuming equipment. However, they do not ignore the cost of energy-consuming equipment that would be incurred in transforming the transportation and industrial sectors. The cost of the capital equipment and durables that consume electricity is dealt with separately in these analyses. A separate cost benefit calculation is made for energy-consuming equipment—one that is common in the evaluation of policies like efficiency standards. The studies estimate the cost of capital equipment, including energy-saving technologies, and compare it to the value of reduced energy consumption. For example, in the case of deep decarbonization in Australia, household personal transportation costs decline by 13 percent from current levels.[17] In deep decarbonization in the United States, total energy service costs (i.e., the cost of the supply of electricity and the cost of the capital equipment that consumes electricity) increase by a net of about 1 percent of GDP.[18]

Focusing on the direct economic cost of generation is justified for several reasons.

- First, given the long-term nature of the transformation, a large part of the investment in energy-consuming equipment and durables involves substitution for investments that would have been made in supply and demand technologies that emit carbon or release other pollutants. The net increase in investment is much smaller than the total investment.
- Second, the direct economic benefits of reducing consumption of fossil fuels, whose price is expected to rise, with fuel-switching and increased efficiency will cushion the blow of the cost of the transformation and help fund the transition.
- Third, choosing the least-cost electricity options can lower aggregate household expenditures on energy services (i.e., the combination of more efficient capital equipment and lower energy consumption levels).

At the same time, the environmental and public health benefits of the transformation do not enter directly into the analysis of the selection of resources. They are not used to justify the expenditure of money to acquire low carbon resources. The low carbon resources selected stand on cost economics.

However, it is important to note that the potential environmental and public health benefits are huge. In the Jacobson et al. analysis, the benefits are almost $5,000 per person per year. The environmental benefits are overwhelming compared to the benefit of fossil fuel cost savings ($170/year).[19] While the environmental and public health benefits are certainly real, relying on them to justify investment in very expensive carbon/pollution reducing technology would raise questions about the economic viability of the low-carbon/low-pollution scenarios. Indeed, the fact that pursuing a low-carbon/low-pollution future "pays for itself" is what the technological revolution is all about.

100 Percent Renewable Roadmap

The 100 percent renewable roadmap in the Jacobson et al. study assumes a robust 5.7 percent per year growth in the business-as-usual demand for energy. It assumes that this level of economic growth could be achieved with a substantial reduction in energy consumption due to the superior efficiency of electricity in transportation and industrial uses. The amount of efficiency improvement in the electricity sector itself (i.e., end-use efficiency) beyond the business-as-usual case is described by the authors as "modest," only 6.9 percent of total demand.[20]

The authors evaluate the economic costs of the renewable resources available in each of the 139 nations and build a portfolio of resources for each nation to meet the assumed need. They have prepared a similar analysis for each of the 50 states in the United States. The constraint is that only low-carbon/low-pollution resources are considered. Fossil fuels, nuclear, and biomass are excluded because they are either carbon-emitters, release other pollutants, or both. Having excluded the high-carbon and polluting resources, the study then includes resources in the "merit order" of their costs.

As shown in Table 2.2, a wide range of utilization is projected for each of the major resources across the 139 nations.[21] This variability supports the approach of applying merit order principles within countries after the high-carbon and high-polluting resources are eliminated. It also supports the approach taken by the Paris Agreement to rely on national contributions to carbon reduction. Jacobson et al. identify a handful of nations that already derive between one-fifth and two-thirds of their energy from the resources included in the environmentally constrained portfolios,[22] which suggests the feasibility of the long-term goal.

Table 2.2 also shows, however, that when all of the different solar technologies and applications are added together, solar is the dominant resource by far in the 2050 resource mix. Wind is the second most important resource. Taken together, wind and solar account for over four-fifths of the resources. Moreover, it is important to keep in mind that in each of the studies, efficiency is assumed to be the least-cost resource and its

Table 2.2 Resource Percentage in Jacobson et al. for all 139 Countries, with Average and Standard Deviation in Percent of Resources

	Jacobson et al.		Greenpeace		Deep Decarbonization
Resource	Average Share	Standard Deviation	Average Share	Standard Deviation	Average Share
PV (Total)	54		39	11	28
Utility PV	42	21			
Residential PV	6	8			
Commercial PV	6	4			
CSP	8	8	11	2	5
Wind (Total)	33		34		36
Onshore	20	13		1	
Offshore	13	13			
Hydro	4	11	7	1	7
Biomass	0	0	3	1	3
Geothermal	1	6	3	1	1
Wave	1	3	2	1	
Fossil w/CCS	0	0	0	0	10
Nuclear	0	0	0	0	9

CSP = Concentrating Solar Power; CCS = carbon capture and storage.

Sources: Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries*, December 13, 2015; Greenpeace International, Global Wind Energy Council, and Solar Power Europe, *energy [r]evolution: A Sustainable World Energy Outlook 2015* (Amsterdam, The Netherlands: Greenpeace International, 2015); Deep Decarbonization Pathways Project, *Pathways to Deep Decarbonization* (Paris: SDSN—IDDRI, 2015).

contribution substantial, but it is not reflected in the analysis of the acquisition of the resources to meet the need for electricity. Efficiency decreases the need exogenously.

Greenpeace Study

The Greenpeace study is similar to the Jacobson et al. study in excluding both high-carbon and high-pollution resources. Table 2.2 shows the average and standard deviation of the two scenarios (cases) in the study. The energy revolution base case assumes 83 percent reliance on renewables. The advanced case assumes 100 percent renewables. As shown in Table 2.2, the mix of generation resources in the Jacobson et al. and Greenpeace studies is similar. There are, however, some significant differences between the studies.

Greenpeace assumes a much higher rate of efficiency improvement. Although the Greenpeace analysis treats sectors separately, making it difficult to compare it directly to the Jacobson et al. study, Greenpeace appears to assume a much larger role for efficiency improvement in end uses—over 40 percent. This is about twice the efficiency assumed in the Jacobson et al. study, when the base-case efficiency improvement and the "modest" end-use efficiency improvement are combined. Greenpeace's higher level of efficiency gain is consistent with current estimates of what is already economically justified.[23] In the long term, the technical potential is much higher. While the assumption of a higher level of efficiency gain is not central to the conclusions of this paper, it provides an important focal point of analysis in Chapter 6.

Deep Decarbonization Pathway Project

While the Deep Decarbonization study shares many key attributes with the two other studies about carbon reduction and the electrification of the broader economy (including the transportation and industrial sectors), there is a major difference. It limits the constraint of resource acquisition to decarbonization and it does not impose a pollution constraint. As shown in Table 2.2, this results in a substantial role for carbon capture and storage and nuclear power. Our analysis below shows that the inclusion of carbon capture and storage and nuclear power is not economically justified because the costs are much higher.

Because the Deep Decarbonization study builds on multiple-country studies, it is difficult to ascertain why these resources end up in the generation portfolio. However, the Australian case provides a possible explanation. That analysis points to a cost study from several years ago that had an extremely low estimate of the cost of nuclear power from new reactors.[24] The most recent updated estimate from essentially the same set of authors more than doubles the projected cost of nuclear, a subject that will be addressed in other chapters. At the current cost, it would not be included in the *Pathway* portfolio. Empirical evidence from the current construction of new reactors around the world shows that the real cost of new nuclear is several times higher than the extremely low industry cost estimates that may have affected the Deep Decarbonization Project estimates. The Jacobson et al. analysis, which also uses an artificially low projection for nuclear costs, avoids making the mistake of including nuclear power in the portfolio by disallowing it due to its high level of other pollutants.

THE PARIS AGREEMENT

Economic Framework

These technoeconomic fundamentals are reflected in the Paris Agreement in several important ways. Urgency and cost are critical concerns in the Agreement.

The Agreement affirms the urgent need to reduce carbon emissions, using the word "urgent" six times. It makes repeated reference to near-term time frames, referencing "2020" a total of twenty times, "2025" four times, and "2030" four times. It draws a direct link between rapid action and the ultimate cost of meeting the challenge, "*emphasizing* the enduring benefits of ambitious and early action, including major reductions in the cost of future mitigation and adaptation efforts."[25]

This urgent call to action reflects the conclusion that current commitments to decarbonization are inadequate, which leads to "the concern that the estimated aggregate greenhouse gas emission levels in 2025 and 2030 resulting from the intended nationally determined contributions do not fall within least-cost 2°C."[26] It also reflects the fact that, in the long term, "greater levels of mitigation can reduce the need for additional adaptation efforts, and that greater adaptation needs can involve greater adaptation costs."[27] Thus, near-term mitigation reduces long-term adaptation and total costs.

The Paris Agreement is progressive in a number of ways, including

- vigorous policies to achieve the goals of access to, and local control of, electricity for developing nations,
- differential contributions from Parties to reflect capabilities,
- transfer of resources from developed to developing nations, and
- a mixed public and private approach.

Timing and technology also must interact with capacity-building (mentioned 49 times) to achieve the benefits of near-term action. The agreement focuses on rapid development and deployment of carbon-reducing technologies and practices (mentioned 44 times). It stresses the early period, noting "the urgent need to enhance the provision of finance, technology and capacity-building support by developed country Parties, in a predictable manner, to enable enhanced pre-2020 action by developing country Parties."[28]

The Agreement requires individual and shared responsibility that reflects the role of economics in the desire to achieve sustainable development (mentioned 16 times) based on nationally determined contributions (mentioned 61 times). The framework for these contributions recognizes "the differentiated responsibilities and respective capabilities, in the light of different national circumstances" (mentioned four times).

It encourages the parties to stimulate broad public participation (mentioned seven times) in the local and global decision-making process, encouraging "the Parties to the Paris Agreement at its first session to explore ways of enhancing the implementation of training, public awareness, public participation and public access to information so as to enhance actions under the Agreement."[29]

The goal of sustainable development is balanced and progressive in the Agreement: "Developing countries . . . are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances."[30] Developed countries not only take the lead in financing and enhancing technology transfer, they "shall continue taking the lead by undertaking economy-wide absolute emission reduction targets."[31] As larger emitters with more resources, they are held to a higher standard.

The lower the cost, the greater the ability to achieve the sustainable development goal. The only generation technologies specifically mentioned in the Agreement are those that are currently being widely deployed: renewables. The Agreement points to the "need to promote universal access to sustainable energy in developing countries, in particular in Africa, through the enhanced deployment of renewables."[32]

The focus on renewables, which use local resources, also furthers other goals of the Agreement, including a desire to promote the "development and enhancement of indigenous capacities and technologies. . . . Exploring how developing country Parties can take ownership of building and maintaining capacity over time and space."[33]

The idea of promoting local ownership, capacity, and resources is embedded in an approach that recognizes the need for flexibility in resources and technology, but also the need to promote a mixed model of public and private involvement in meeting the challenge of climate change. Treating climate change as a commons/externality challenge generally supports an active role for public policy. An important task highlighted in the Agreement is to develop and integrate nonmarket approaches.

> To incentivize and facilitate participation in the mitigation of greenhouse gas emissions by public and private entities authorized by a Party . . . [and] recognize the importance of integrated, holistic and balanced nonmarket approaches being available to assist in the implementation of their nationally determined contributions, in the context of sustainable development and poverty eradication, in a coordinated and effective manner. . . . These approaches shall aim to . . . (b) Enhance public and private sector participation in the implementation of nationally determined contributions; and (c) Enable opportunities for coordination across instruments and relevant institutional arrangements.[34]

Another extremely important aspect of the governance model is the outreach to subnational and non-party entities, with an offer of observer status. Although states are vested with treaty-making power, the Paris Agreement recognizes and encourages the participation of other entities (31 times) including subnational entities (governmental and nongovernmental, 12 times) and encourages non-signatories (12 times) to participate through observer status (7 times).

The academic literatures on energy efficiency and climate change strongly supports the general approach and economic principles embodied in the Paris Agreement:

- least-cost measures should take precedence,[35]
- mitigation costs are smaller than adaptation costs,[36]
- early action lowers the transitional and total economic cost of decarbonization dramatically,[37]
- early action that lowers costs requires targeted and induced technological change,[38]
- institutional capacity is crucial to effective, least-cost implementation,[39]
- technology transfer and learning play a vital role in meeting the challenge in a cost effective manner,[40]
- flexible, overlapping policies are needed that recognize both localism[41] and complexity,[42] and
- sustainable development must be the cornerstone of the response to climate change.[43]

Governing the Climate Commons

A brief description of the political governance structure of the Agreement rounds out the description of its political economy. The governance structure establishes how resources will be selected and judged in the effort to meet the challenge of climate change. We view the governance structure of the Paris Agreement as a commons governance model based on a multistakeholder approach that delegates responsibility to local authorities (i.e., applies the principle of subsidiarity).[44] The Agreement defines the challenge of climate change as a commons problem (used 7 times) in need of a collaborative/coordinated solution (used 14 times). It intends to elicit the appropriate responses with intensive exchange of information (mentioned 43 times).

The Agreement's approach to governance can best be described in terms of the elements of a successful common pool resource management model. Just as we have argued that the current state of academic research is well-reflected in the economic structure of the Agreement, so too can it be argued that the governance structure reflects the current state of the academic research. Over the course of the past half century, the viability—and in some circumstances, the superiority—of the collaborative approach to common pool resource management has been widely recognized, culminating in the award of a Nobel Prize in Economics to one of its leading practitioners, Elinor Ostrom.

The following are key elements of the common pool resource management model. They are derived from Ostrom's analysis and framed as challenges or questions to which the management system must respond.[45] The Paris Agreement is described in terms of the answers it provides.

Constitutional rules govern the way the overall resource system is constituted; particularly how collective choice rules are defined. How does the resource system come into existence? **Paris Agreement:** The governance of the common pool resource system is created by the United Nations Framework Convention on Climate Change.

Collective choice rules embody the procedures by which the operational rules are changed. How can the operation of the system adapt? **Paris Agreement:** The Parties, acting through a summit and meeting process, have the authority to adapt and improve the operational rules (as happened in Paris in 2015).

Operational rules govern the activities that take place within the borders of the resource system. How does the system work? **Paris Agreement:** Being based on a convention, it has the trappings of a traditional international agreement, but the dynamics of its governance—the operational rules—resemble the institutions of a traditional common pool resource system.

Boundary rules specify how participants enter or leave their positions. How are users awarded rights? **Paris Agreement:** The set of commoners is defined as the Parties to the Convention, which is the province of nations. Nations also have primary responsibility for local energy policy.

Position rules associate participants with an authorized set of actions. Who gets to use the resource and who oversees it? **Paris Agreement:** Contributions to decarbonization are required. Strategies are defined by individual Parties and must be consistent with the shared goal.

Aggregation rules specify the transformation function to map actions into outcomes. How is the resource measured and controlled? **Paris Agreement:** The responsibility attached to each commoner is both individual and shared. The nations define their contributions and are subject to a collaborative review of the appropriateness of the contribution. Consideration is given to the capabilities of the individual nation and the likelihood that the combined effect of the individual contributions will achieve the shared goal.

Authority rules specify which sets of actions are assigned to positions and how those actions will be overseen. How are users allowed to exploit the resource? **Paris Agreement:** The Agreement follows the principle of subsidiarity, delegating responsibility to self-organized, self-governing policy sectors (i.e., nation states).

Payoff rules specify how benefits and costs are required, permitted, or forbidden in relation to players based on the full set of actions taken and outcomes reached, as well as how the provisioning and maintenance of the resource system will be provided. What are the incentives, taxes, and fines that elicit proper behaviors? **Paris Agreement:** At a high level, the principles for the distribution of both burdens and rewards are laid out. The Paris Agreement is aggressively progressive, in both laying a heavier burden on developed Parties to reduce emissions, and in helping developing Parties achieve the dual goals of development and decarbonization.

Scope rules specify the set of outcomes that may be affected. How do actions impact the resources and other users? **Paris Agreement:** The Agreement adopts a more aggressive target for minimizing temperature increases, which drives the steps necessary to achieve the outcome.

Information rules specify the information available to each position for purposes of monitoring and enforcing compliance with the rules.

> What flow of information best encourages, manages, and distributes the resources? **Paris Agreement:** The Paris Agreement seeks to hold the Parties accountable by establishing effective monitoring and accountability. It outlines a great deal of continuous reporting and information exchange to promote transparency and facilitate the application of social pressures to elicit compliance. In this regard, the Agreement calls for immediate and ongoing efforts to continually assess and refine the goals and relationships.

Given the central policy role of the state, the great diversity of capabilities, and differences in resource endowment, a flexible, collaborative approach was necessary. While concerns have been expressed about a lack of force, it is difficult to see how that force would be mobilized in the absence of a single, overarching authority. It is also the case that common pool resource systems frequently rely on reciprocity in commitment and graduated sanctions. Much work has been done to document the ability of individuals to develop effective management without the imposition of traditional property relations and governmental authority at the level of fairly small, local resource systems. More recent work (and Ostrom's Nobel speech) identified larger-scale resource problems as a nested set of authorities.

The policy challenges that Ostrom derives from her work on common pool resource systems are the challenges that the Parties to the Paris Agreement face.

> Extensive empirical research leads me to argue . . . a core goal of public policy should be to facilitate the development of institutions that bring out the best in humans. We need to ask how diverse polycentric institutions help or hinder the innovativeness, learning, adapting, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales.[46]

The goal is to find polycentric modes of governance that fall between the market and the state, in which a community self-organizes to build institutions based on trust, legitimacy, and transparency. One aspect of the problem of scale that is important to successful management of the commons (to which the Agreement devotes a great deal of attention) is information.[47] Supportive, large-scale institutions can play a key role.[48] The effort to coordinate across vertical governance levels and horizontal policy centers is central to the success of the management of a large commons. The Paris Agreement is a response to these challenges. The theory is correct; it remains to be seen if the practice develops.

PROGRESS AND THE DEVELOPMENT-DECARBONIZATION DILEMMA

This section puts the dilemma of development and decarbonization in the historical perspective of long-term progress, highlighting the immense ability of technology to sustain development, but also the unique challenges that technological revolutions pose. The challenge of development with decarbonization is the result of a remarkable period of improving material conditions, resulting from technological progress that is unprecedented in human history. Just as the problems of economic inequality and climate change were caused by technological progress, the most effective—and perhaps only—way to navigate between the horns of the dilemma is for policy to promote, foster, and guide another technological revolution. We argue that progressive capitalism has seen repeated successes in doing just that, and therefore it is the best candidate system to overcome the development/decarbonization dilemma. Therefore, the starting point must be an appreciation of the progress that has been made and the challenges it has created.

Remarkable Progress

Aggregate measures of progress, population, and gross domestic product have been frequently noted. For centuries, economic and population growth were virtually nil. In the late Middle Ages, growth picked up slightly, but it was not until the Industrial Revolution that it took off. American economist Douglass North pointed to population, since the ability to support a growing population is an indicator of systemic success. However, the close correlation between GDP per capita and energy consumption per capita was also a focal point of his analysis. North focuses on the "the explosive increases in population since the beginning of the modern age in the eighteenth century," as well as "major development in knowledge, technological progress, and scientific breakthroughs that contributed to this explosive development."[49]

The upper graph of Figure 2.2 provides empirical evidence on major economic and social aspects. The lower graph provides empirical evidence on the technologies that underlie the dramatic increase in population by identifying changes in important underlying aspects of development in power and transportation technologies. The rates of growth shown are compound annual increases over a long period—one or two centuries—depending on the data available.

Three of the recent examples involve energy: steam, internal combustion engine, and electricity. Substituting mechanical power for human/animal power and primitive natural sources constituted a major leap that fueled the first Industrial Revolution. The shift to electricity (considered a general-purpose technology) was one of the key factors in the second Industrial Revolution.

It is important to keep in mind that the graph in Figure 2.2 is truncated. Prior to the year 1400, the rate of growth in the factors that affect material well-being was almost nonexistent. The data underscore the immense progress made in material living conditions in the last quarter of a millennium. The dramatic change in the rates of progress is coincident with the emergence of capitalism and the Industrial Revolution.

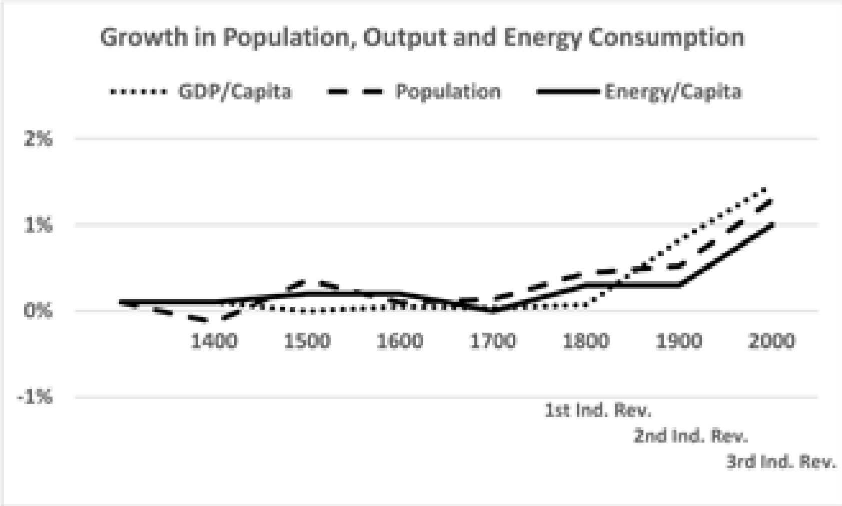
The key message for the purpose of this analysis is strikingly clear. If we accept the proposition that human civilization dates back about 12 millennia, then the capitalist era is about 4 percent of human history. The industrial era covers the latter part of that period. Measured by population, per capita income, heat, power, transportation, and lighting, about 90 percent of human material progress has taken place in the most recent 2–3 percent of human history—the very short period of capitalist industrialization.

THE DECARBONIZATION/DEVELOPMENT DILEMMA

The Development Horn of the Dilemma

This revolution in material conditions has dramatically changed the terrain of human aspirations and distributive justice. For the billions of people who do not yet enjoy the fruits of this economic progress, the aspiration to achieve a standard of living that enables them to thrive in the 21st-century economy represents the developmental horn of our dilemma.

- The industrial revolution has created the possibility/hope/expectation that there will be dramatic continuous improvement in the material well-being of people and freedom from endless poverty.
- The improvement in material well-being comes with (and is partly dependent on) an increasing global interdependence of economic activity (and a refined division of labor and globalization), and it has been driven by capitalist market economies.
- Increasing wealth and improvements in communications (which are made possible by changes in energy technology, i.e. electrification) have allowed more people to engage and participate more directly and forcefully in self-governance.
- For the past quarter of a millennium, the groundwork for a higher standard of living has been laid by each successive generation. The



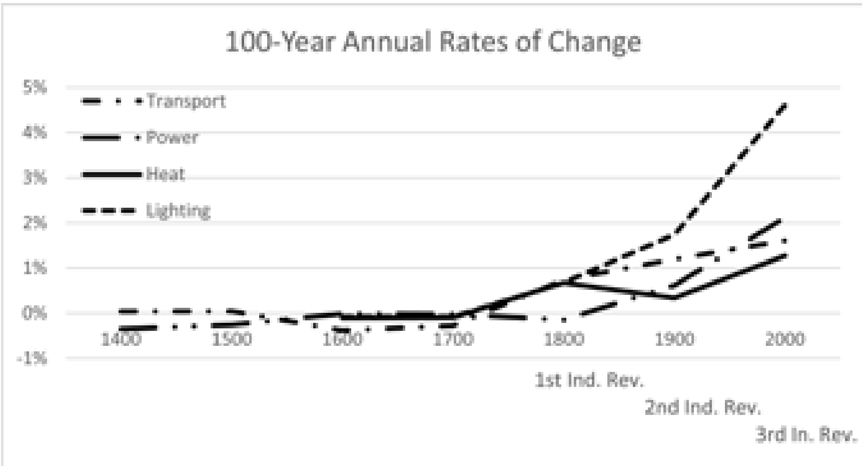


Figure 2.2 Industrial Revolution Annual Rates of Economic Growth and Improvement in Energy Technology Output

Sources: Upper graph based on Douglass C. North, *Understanding the Process of Economic Change* (Princeton, NJ: Princeton University Press, 2005), 89; U.S. Bureau of the Census, https://www.census.gov/populaton/international/data/worldpop/table_history.php (UN 1999 where available, average of lower and upper summary elsewhere); Wikipedia, https://en.wikipedia.org/wiki/World_population_estimates; J. Bradford De Long, "Estimates of World GDP, One Million B.C.—Present; Standard Chartered," *Technology: Reshaping the Global Economy*, January 19, 2015, 11. Lower graph based on data from: Benjamin K. Sovacool and Michael H. Dworkin, *Global Energy Justice: Problems, Principles, and Practices* (Cambridge, U.K.: Cambridge University Press, 2014), 48 and 312, heat, light, transportation, power; De Long, "Estimates of World GDP," 11.

current generation should not be chastised for over-consuming scarce resources as long as it produces the means to maintain and improve the prospects of future generations.

- The dilemma confronting the political economy is that it must now sustain and spread economic growth without emitting carbon or pollution.

The development horn of the dilemma is described in Figure 2.3. Although economic growth has been extremely high on average for a quarter of a millennium, economic development across the globe has been

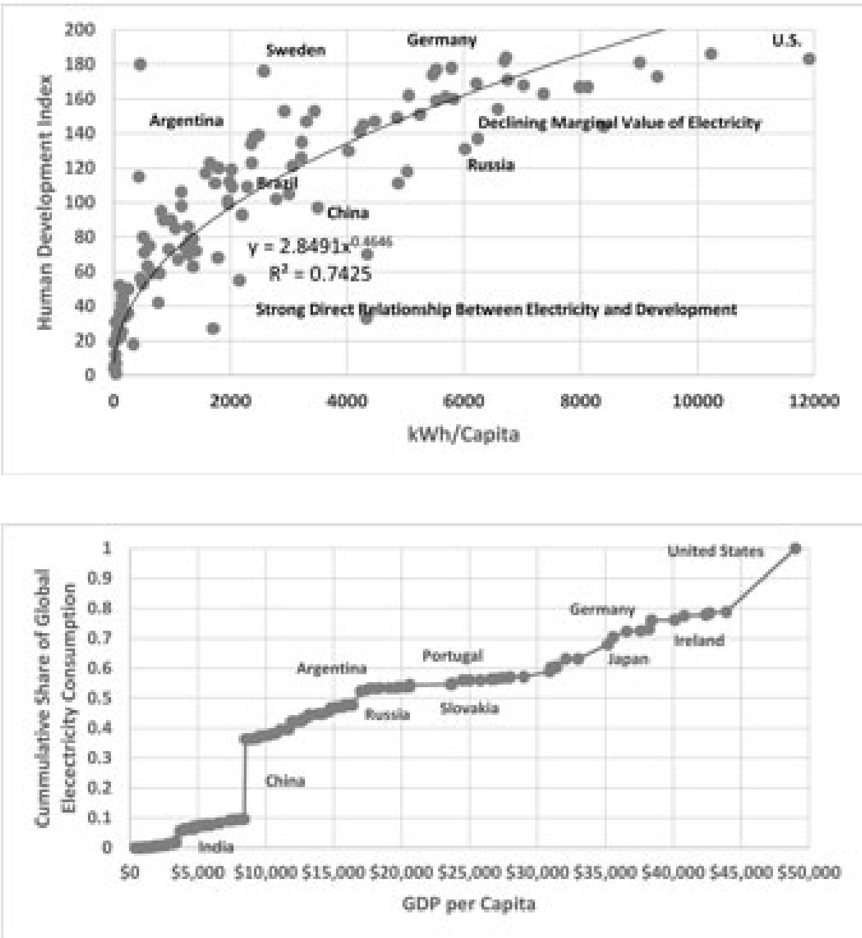


Figure 2.3 The Climate Change Dilemma of Development and Decarbonization

Source: http://www.wri.org//blog/2014/05/history-carbon-dioxide-emissions.

very uneven. The graph shows the relationship between human development and per capita electricity consumption per year, with the nation state as the unit of analysis. In this analysis, we exclude a small number of outliers that exhibit atypical characteristics. The criteria are incomes above $50,000 per capita, and consumption above 12,000 kWh per capita. This eliminates several small island nations, small oil states, and extremely cold climates, but 97 percent of the global population remains in the analysis.

Two important relationships are highlighted by Figure 2.2. First, a large number of nations are at quite low levels of development and electricity utilization. Second, there is clearly a declining marginal increase in development as consumption rises. Similar relationships can be shown for GDP, life expectancy, and well-being, with cultural differences affecting the strength of the relationship. While there is clearly variation in electricity consumption at any given level of human development, the underlying correlation is strong, accounting for three quarters of the variance (r^2=.74). The same is true to a slightly lesser degree for other measures of performance including gross domestic product (r^2=.67), rank on well-being (r^2=.65) and longevity (r^2=.55).

The lower graph shows the cumulative distribution of greenhouse gas emissions and GDP per capita. Key nations identified now as “bumps” in the curve represent those with major contributions to emissions: India and China, because of their very large population; and Russia, Japan, and the United States, because of the combination of relatively large population and high levels of consumption. Eliminating the outliers puts the United States at the highest level. The other nations identified on the curve represent levels of GDP and consumption that are of interest in considering the challenge of climate change, as discussed later in this chapter.

Deciding what level of economic development is “good enough” for purposes of studying the extent of growth from below, and degrowth from above, is a subjective and daunting task.[50] Here, it suffices to say that the developmental horn of the dilemma stems from the fact that, measured by GDP per capita adjusted on a purchasing power basis, the dispersion is quite large.

The debate between those who argue that sustainable growth is or is not possible within the limits of the resources of the global ecosystem can fill (and has filled) volumes. This book accepts the two horns of the dilemma—the need to meet the aspiration of the vast majority of people for higher standards of living than they now have, while simultaneously decarbonizing and depolluting the economy. No amount of squeezing the living standard at the top will make room for expansion at the bottom and in the middle. The solution is environmentally benign technological change. Capitalist industrialization, which has created an immense amount of human progress while allowing a great deal of unnecessary excess, has already produced the cornerstone of the solution, as it has numerous times over the quarter-millennium of its existence. The solution is the remarkable improvement of renewable and distributed technologies to produce electricity, and the combination of information communications and advance control technologies to reduce and manage demand technologies that are needed.

While the technoeconomic tools are in hand, the socioinstitutional structure to apply them is not. That is what the fierce debate is about. The book argues that capitalist industrial revolutions have avoided the dire fate that some see as inevitable by turning in a progressive direction. The Paris Agreement is exactly the right step in that direction.

Thus, this view not only triggers all of the animosity of the growth/degrowth debate, but it also triggers the equally intense debate between the *laissez faire* market fundamentalists and the anticapitalists. Progressive capitalism is the political economy that provides the solution. Capitalism is needed to solve the economic problem of sustaining, low-carbon, low-polluting development, and progressive policies are needed to solve the political problem of meeting the widespread aspiration for a better quality of life.

As a problem of political economy, building the new system is an intensely conflicted process and the outcome is uncertain. That is all the more reason to be crystal clear at the outset about the model of political economy we are advocating. Throughout the book, we make the case that this is the correct direction to be heading, and these are the challenges that will have to be overcome to arrive at the desired end point. Since we have defined the political economy we advocate and presented the evidence in its support, we will not spend time justifying and locating it within the broader debate. Here, we only point out that this nuanced position has support in the debate—support that seems to be growing.[51]

The Decarbonization Horn of the Dilemma

The consumption of fossil fuels, which has powered dramatic economic growth, has also produced a massive increase in the greenhouse gases that are causing climate change. Contemporary GDP and consumption of electricity are a good indicator of greenhouse gas emissions, although the mix of generation sources and other uses of fossil fuels are important in determining the total emissions in a given nation. On a historic, cumulative basis, the distribution of fossil fuel emissions establishes the pattern to decarbonize the economy. The lower graph in Figure 2.2 shows the distribution. The correlation between current electricity consumption and greenhouse gas emissions is .97. While this is "just" a correlation, it is relevant and useful. The level of penetration and use of electricity reflects the long-term development of material conditions within nations, and electricity is the master energy form in the 21st century. It will become more so as decarbonization proceeds. The correlation reflects a cause and effect relationship in addition to being highly relevant for both development and decarbonization policy.

THE LIMITS OF REDISTRIBUTION AND THE NEED FOR TECHNOLOGICAL INNOVATION

Substitution of nonfossil resources in electricity generation, and electrification of the transportation and the industrial sectors, are major technological responses to the challenge of climate change that will be discussed in the book. Here we focus on the question of how far changing the distribution of consumption goes toward solving the development/decarbonization dilemma, holding technology constant. A paper by Fritz and Koch that addressed this issue provides the starting point for the analysis. The upper part of Table 2.3 shows the nations and groupings they analyzed. The lower part of the table shows data we have gathered to analyze further the growth-energy consumption, decarbonization issue.

Fritz and Koch find that economic development is the key to "prosperity," but the relationship is complex and not linear.

> This paper aims at empirically identifying structural potentials and policy challenges for prosperity at scales where economic development remains within ecological carrying capacities. Building on the growing literature that interprets prosperity "beyond" economic growth, the paper presents a three dimensional concept to operationalize prosperity in terms of ecological sustainability, social inclusion, and the quality of life. . . . The results of cluster and correspondence analyses indicate the existence of five "prosperity regimes" and demonstrate that all aspects of prosperity—including (unsatisfactory) ecological performance—are linked to economic development. However, our findings also indicate that in order to achieve a decent minimum of prosperity moderate levels of the material living standard are sufficient. Further increases in the material living standard do not lead to significant additional prosperity; instead they cause greater environmental harms.[52]

Table 2.3 Development, Energy Consumption and Carbon Emissions, Clusters of Countries: Circa 2010

Fritz Clusters	1	4	5	3	2
Economic development GDP ($ per capita @ Purchasing Power Parity, PPP)	17,778	18,012	26,083	39,319	46,268
Ecological sustainability CO_2 (tons per capita)	3.2	9.2	7.9	7.8	12.7
Ecological footprint (global hectares per capita)	3.2	3.3	5.1	5.2	7.0
Social inclusion (Gini Index)	47.8	41.1	30.0	31.1	29.3
Homicide rate (per 100,000 persons)	10.6	5.1	1.6	0.9	1.6
Democracy Index (0 = low, 10 = high)	7.2	3.7	7.7	8.4	9.0
Freedom in the World Index (1 = low, 7 = high)	5.1	1.0	5.8	5.9	6.0
Quality of life, Life expectancy (years)	76.8	72.9	78.4	81.8	80.7
Well-being (0–10)	6.5	5.1	5.7	6.9	7.4
GDP growth	3.7	5.6	−0.3	0.7	0.5
Unemployment (percent)	6.9	5.0	14.0	7.2	6.5
Nations	Argentina	China	Czech Republic	Austria, Sweden	Australia
	Brazil	Russia	Estonia	France, Switzerland	Belgium
	Chile		Greece	Germany, U.K.	Canada

			Costa Rica		Hungary, Poland	Ireland	Denmark, Finland
			Mexico		Portugal, Slovakia	Israel, Italy, Norway	Netherlands, Japan
			Turkey, Uruguay		Slovenia, Spain	South Korea	United States
						New Zealand	
Cooper Data	**China**	**Turkey**		**Russia**			
GDP/Capita	$8500	$14,700	$14,900	$17,770	$25,600	$35,200	$48,000
Kwh/Year	3494	2019	2,500	6018	4,900	6,700	11,400
Kwh/$1000GDP	4100	1370	1680	3400	1900	1900	2380
2012 % of World GHG emission	22%		7%	5%	2%	6%	18%
Nations at Key Thresholds	**Global Below Median**	**Median**	**Argentina**	**Portugal**		**Germany**	**United States**
GDP/Capita	$3300	$8,500	$17,700	$23,800		$38,400	$49,000
Kwh/Year	493	1400	2,500	4500		6200	12000
Kwh/$1000GDP	1410	1650	1410	1890		1610	2450

Sources: Martin Fritz and Max Koch, "Potentials for Prosperity Without Growth: Ecological Sustainability, Social Inclusion and the Quality of Life in 38 Countries," *Ecological Economics* 108 (2014), Figure I-3. http://www.wri.org//blog/2014/05/history-carbon-dioxide-emissions; https://en.wikipedia.org/wiki/List_of_countries_by_electricity_consumption; https://en.wikipedia.org/wiki/List_of_countries_by_GDP_(PPP)_per_capita; https://en.wikipedia.org/wiki/List_of_countries_by_population_(United_Nations).

Fritz and Koch identify five clusters of countries at various levels of development with different carbon footprints and other social and political performance. Cluster 4, made up of China and Russia, is quite heterogeneous. While the income level is close to the first cluster, these two nations have high carbon footprints, low democracy, and low well-being indices. China is well below the "lowest" prosperous nation on economic development, and Russia is just at that prosperity level. Cluster 4 is not a useful target. Assuming that the highest cluster is "too" high, this analysis considers Clusters 1 and 5 as potential "targets" for growth and degrowth.

We have added the GDP, electricity consumption, and GHG emissions data from Figure 2.2 to the bottom of Table 2.3. The thresholds of consumption/development identified in Table 2.3 are then defined by individual nations in each of the three clusters. We believe the concrete referents provide a better sense of the standard of living.

As income increases, electricity consumption increases pretty much in a linear fashion until the wealthiest group. China and Russia have very high rates of electricity consumption per dollar of GDP. Many of the former Eastern bloc nations also have very high levels. Argentina is very efficient, producing a GDP more than twice the median with a level of electricity consumption that is considerably less than twice the median. Portugal is less efficient, with slightly less than three times the median income and slightly more than three times the electricity consumption. Germany is about 9 percent above the group median on income and 9 percent below the group median on electricity consumption, which makes it almost 20 percent more efficient at creating income per kwh of electricity consumed.

The general nature of the challenge can be seen in the percent of greenhouse gases from each cluster. Using Argentina as the threshold, the countries above it represent only one-quarter of total global emissions. If more than an 80 percent reduction in carbon emissions is needed from current (or recent) levels, and a great deal of economic development is needed in the material conditions for the nations below, redistribution through degrowth will fall far short. The response to climate change needs to do more than squeeze the consumption of the wealthiest nations—it needs to also create paths to growth with much lower levels of emissions.

This message is conveyed in Table 2.4, which considers three scenarios for the global need of low-carbon resources with two levels of development "targets." The table calculates the increase in electricity consumption that would be required to achieve the target level for those below the threshold, assuming the historic level of consumption in the target nation. It also shows the decline in the amount of electricity (emissions) if the

Table 2.4 Scoping the Magnitude of the Dilemma, Circa 2010

			% Change in Electricity Need from Current Level					
Threshold of income	Annual kWh	Number of People (Million)	Equalizing % change from		Electrification of Transport & Industry	Net Change %		
			Growth	Degrowth		Growth Only		Annual Avg. w/80%
Below			Below	Above		Total	Avg. Annual	Decarbonization
Argentina	69	4563	+44	–32	+150	+162	+2.8	+3.6
Portugal	1637	6019	+94	–13	+150	+231	+3.5	+4.1

Source: Author calculation, see text.

nations above reduced their consumption to the target level. This represents the development horn of the dilemma. Focusing only on the electricity sector at the level of the standard of living and electricity consumption of Argentina, squeezing consumption above might "make room" for emissions below, but it would still be a considerable challenge to bring emissions down to the target levels.

With the additional burden of decarbonization of the transportation and industrial sectors, the deficit becomes huge. The rate of improvement in efficiency needed to sustain the level of economic development and decarbonization rises steadily as the target threshold is raised to almost 5 percent per year. The technological challenge is great, but the past rates of technological improvement identified in Figure 2.1 are in line with the need identified in Table 2.4. We observe that over the past century, lighting (an electricity-based service) and power achieved a level of improvement in the range of 2 to 4 percent. Table 2.4 identifies a maximum net annual average change in electricity that is just over 4 percent with 80 percent decarbonization.

A zero-carbon electricity sector based on a technological revolution is on the horizon and being widely discussed. In other words, a technological revolution on the scale of the second Industrial Revolution will be needed to pass through the horns of the dilemma.

CONCLUSION

This chapter has briefly reviewed two key factors that define the context for electricity resource selection in the 21st century—the political decision to decarbonize, and the technological revolution that has made it possible to pursue that goal while continuing to pursue the goal of development. While renewables are clearly the core of a decarbonized electricity sector, the seeds of the ongoing debate between advocates for renewables and those for 20th-century central-station generation can be seen in the side-by-side scenarios in Table 2.2. Even a 10 percent market share for a technology in the expanded electricity sector represents a very substantial amount of economic activity, and as shown below, substantial excess cost. This debate continues to be intense, not only because of the economics discussed in Chapter 1, but also because there is a fundamental difference and incompatibility between the nature of electricity systems necessary to optimize the performance of the two types of technologies, as discussed in Chapter 6.[53]

The analysis of development is not meant to disregard the role that responsible growth (or degrowth) can play in responding to the challenge of climate change. It indicates that if the aspiration for a higher standard of living is going to be supported, then technology is the key tool for navigating the dilemma. The empirical analysis, policy debates, and academic literature reviewed in this book reflect a fundamental debate between three positions: *Laissez faire* markets; active, progressive policy to direct, smooth, and speed market reactions; and abandonment of the market altogether in favor of a nonmarket (socialist) approach.

Unlike the ecological economics literature, we argue that market imperfections are not the justification for abandoning the market approach to economic challenges, but rather they are the justification for imposing constraints on market outcomes and implementing policies to direct the market in the necessary direction. Progressive capitalism lives in the space between *laissez faire* economics, which argues the market will take care of everything once greenhouse gas emissions are taxed, and the anticapitalists, who argue that capitalist markets cannot be part of the solution.

Indeed, within the framework of this paper, approaches like smart growth, smart grid would reinforce the processes of innovation and investment to support a high living standard with lower carbon emissions as decarbonization proceeds. We argue that the role of a carbon price is an important secondary supporting factor in the economy. We also argue that degrowth, incorporated into the common-sense paradigm of the 21st-century electricity system, would play an important secondary role in the socioinstitutional structure by supporting the policy of progressive efficiency in meeting needs, rather than infinite growth. It can be reasoned that the early degrowth advocates who argued for a steady state economy had this in mind.[54]

In this book, we make the case that the progressive capitalist approach is superior for economic reasons, preserving the engine of innovation and investment, while moving the market to a more equitable distribution. However, progressive capitalism is also superior for political reasons. If the political force necessary to eliminate capitalist markets existed, there would be more than sufficient force to drive capitalist markets in a progressive direction. Moreover, the political force necessary to reform capitalism by driving it in a progressive direction would likely be substantially less than the political force necessary to overthrow it altogether. Pragmatic, progressive capitalism is both economically preferable and politically more doable.

PART II

ANALYTIC FRAMEWORK

3

THE TECHNOLOGICAL REVOLUTIONS OF INDUSTRIAL CAPITALISM

INTRODUCTION

A successful political economy stands on two pillars: a technoeconomic paradigm that creates material resources to sustain its population, and a socioinstitutional paradigm that organizes those people into stable economic, social, and political relationships. Therefore, a coherent theory of political economy that explains its ability to succeed needs an economic model, a moral framework, and an analytic method that illuminates the process by which policy and politics have operated to create viability.

In this chapter, we describe the building blocks of progressive capitalism and outline the processes that underlie its success. That discussion of success—described in Part I of this book as the technological revolution making a low-carbon economy possible—is only half of the story of progressive capitalism, however. The other half is the persistent and pervasive imperfections that afflict capitalism, which must be addressed by active policy. As shown in Table 3.1, there have been a number of schools of thought that have received numerous Nobel Prizes in economics over the past quarter century, which highlight these market imperfections. These critiques of market fundamentalism are listed according to the factors that affect the performance of the political economy, which are at the heart of the analytic framework that guided U.S. progressive capitalism in its heyday—the Structure/Conduct/Performance paradigm. The discussion of policy in Part V reflects this framework.

These schools of thought can also be seen in a range of widely praised, empirically oriented frameworks. At the macro level of historical analysis, theses authors argue that markets and the state have been intricately

Table 3.1 New School of Thought Enriching the Understanding of Market Imperfections as the Basis for Progressive Policy: A Quarter Century of Nobel Economics Prizes

S-C-P Factor	New School of Thought
Basic Conditions:	**New Institutional/Transaction Cost Economics:** Ronald Coase, 1992; Douglas North, 1993; Robert Fogel, 1993; Oliver Williamson, 2009; Elizabeth Ostrom, 2009
	Endemic Flaws: Joseph Stiglitz, 2001; Michael Spence, 2001
Market Structure:	**Deeper Critique of Structural Imperfections:** Paul Krugman, 2008; Jean Tirole, 2014; James Heckman, 2008; Angus Deaton, 2015
Conduct:	**Behavioral Economics:** George Akerloff, 2001; Daniel Kahneman, 2002; Vernon Smith, 2002; Robert Shiller, 2013.
Performance:	**End of Value Free Economics, Return of Political Economy:** Amartya Sen, 1998; and all of the above

Sources: Nobel Laureate lectures can be found at: http://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/.

intertwined in creating a quarter-millennium of unprecedented progress in the economy. This explanatory and policy paradigm is best described as progressive capitalism, wherein capitalist markets stimulate entrepreneurship, innovation, and investment when enabled by policies that set the critical conditions for market and economic success. Neoclassical economics recognizes some very limited sources of market failure that need to be corrected with policy. In contrast, the progressive capitalist view not only identifies many more market failures and imperfections, but also identifies the key role of public policy (the state) in creating the conditions for market success. The state does not simply act as a policeman passively waiting to correct problems if they arise (they rarely do in the neoclassical view); it actively guides the economy toward a trajectory of stable growth by recognizing the need for a balance between public and private interests, and fair distribution of resources to support an ever expanding division of labor.

The thrust of these alternatives challenges market fundamentalism by demonstrating and insisting on the important role of the state and policy, and rejecting the notion of value-free economics. Therefore, we describe progressive capitalism in reverse order, starting with the role of the state in the political economy, then outlining the moral framework that holds it together, and ending with a discussion of the market.

FRAMEWORKS OF PROGRESSIVE CAPITALIST DEVELOPMENT

Historical Periodization

Because the alternative theories are historically grounded, it is important to start with the historical patterns that appear to exhibit regularities, which become the processes to be explained. Periodization is the key to recognizing repetition of similar patterns (see Table 3.2). Pérez identifies three primary periods (installation, turning point, and deployment) that are composed of eight sub-periods (big-bang, irruption, frenzy gilded age, bubble, recession, synergy, golden age, and maturity), with each period defined by the major economic activity taking place. In this framework, five technological revolutions within the capitalist industrial revolution have been identified by distinct technologies and leading nations. Table 3.3 shows three key processes that compose the revolution: the design/innovation stages and processes, the financial processes, and the sociopolitical development process.

For each of the five technological revolutions, we note the prime-mover source of energy. The initial capitalist revolution was pre-industrial, driven by wind and water (mills, sailing ships, and canals). The first Industrial Revolution was driven by steam (coal). The second was driven by oil and electricity. We identify decarbonization as the potential transformation for the phase of institutional recomposition. The energy transformation comes later in the process and reflects a fundamental change in the political economy.

Historical Process

The observation of repeated patterns of technological change, economic upheaval, and stable growth lead to higher-level generalizations about the historical process; not inevitable outcomes, but clear tendencies or pathways that can be pursued by policy. Figure 3.1 presents summaries of two approaches for analyzing the process of technoeconomic change that afford the state and policy a large role. Both of the approaches rely on the concept of creative destruction, and both describe the process of creative construction that takes place in its wake. Thus, they are neo-Schumpeterian (emphasizing the role of innovation and creative destruction) and post-Keynesian (highlighting the importance of inclusion and demand support).[1] They lie squarely in the new institutional realm,[2] with the state playing a central role in the process—one that changes over the life cycle of the political economy.

Table 3.2 Empirical Description of Five Industrial Technological Revolutions

Periodization									
Great Surge		**Installation Period**			**Turning Point**	**Deployment Period**			
Technological Revolution	**Core Nation**	**Big-Bang**	**Irruption**	**Frenzy Gilded Age**	**Bubble**	**Recession**	**Synergy**	**Golden Age**	**Maturity**
1st The Industrial Revolution	Britain	1771 Arkwright's mill opens	1770s–early 1780s	late 1780s–early 1790	Canal mania	1793–1797	1798–1812	Great British leap	1813–1829
2nd Age of Steam & Rail	Britain	1829 Rocket steam engine	1830s	1840s	Railway mania	1848–1850	1859–1857	The Victorian Boom	1857–1873
3rd Age of Steel & Heavy Engineering	Britain, USA, Germany	1875 Carnegie Bessemer Steel	1875–1884	1884–1893	Global Infrastructure build-up	1893–1895	1895–1907	*Belle Époque* Progressive Era	1908–1918
4th Age of Oil, Autos and Mass Production	USA	1908 Model T	1908–1920	1920–1929	Roaring '20s, Autos, Housing, Radio, Aviation, Electricity	1929–1943	1943–1959	Post-war Golden Age	1960–1974

5th The ICT Revolution	USA	1971 Intel Microprocessor	1971–1987	1987–2001	Dotcom & Internet mania, Financial Casino	2000 2007–2008	20?? ↑ WE ARE HERE	Sustainable global knowledge-society "golden age"; Decarbonization sun, wind, & water

Source: Adapted from Mark Cooper, "The ICT Revolution in Historical Perspective: Progressive Capitalism as a Response to Free Market Fanaticism and Marxist Complaints in the Deployment Phase of the Digital Mode of Production," *Telecommunication Policy Research Conference Session on Innovation*, September 28, 2015; based on Carlota Pérez, "Financial Bubbles, Crises and the Role of Government in Unleashing Golden Ages," in *Innovation and Finance*. Edited by A. Pyka and H. P. Burghof (London: Routledge, 2013); Carlota Pérez, "Technological Dynamism and Social Inclusion in Latin America: A Resource-Based Production Development Strategy," *CEPAL Review* 100 (2010); Carlota Pérez, *Technological Revolutions and Techno-Economic Paradigms*. Working Papers in Technology Governance and Economic Dynamics, January 2009; Carlota Pérez, "Finance and Technical Change: A Long-Term View," *African Journal of Science, Technology, Innovation and Development*, 3 (2001), 13; Carlota Pérez, "Re-Specialization and the Deployment of the ICT Paradigm: An Essay on the Present Challenges of Globalization," in *The Future of the Information Society in Europe: Contributions to the Debate*, ed. R. Compañó et al. Technical Report EUR 22353 EN, Institute for Prospective Technological Studies, 2006, 39.

Table 3.3 Technological, Financial, and Sociopolitical Processes in Industrial Technological Revolutions

Periodization	**Installation Period**			**Turning Point**		**Deployment Period**			
	Big-Bang	**Irruption**	**Frenzy Gilded Age**	**Bubble**		**Recession**	**Synergy**	**Golden Age**	**Maturity**
Processes									
Technoeconomic Paradigm	Design open		Trajectory defined					Trajectory constricted	
	Radical Innovation	Initial optimization	Exploratory improvement	Incremental Innovation	Successive improvements of models	Systemic application of innovation criteria		Last few improvements	Market Saturation
Finance	Public Seed \ Venture Capital		Intensive Investment		Coherent growth with increasing externalities production and employment				Diminishing returns to innovation
				Financial bubble, Decoupling real of financial economy					
Sociopolitical Institutions	Start of revolution		Techno-economic split			Institutional Recomposition			
Conflict				Incumbent resistance to change					
					New entrant resistance to restraint				
			Polarization of rich and poor						
				Sociopolitical split					

Source: see Table 3.2.

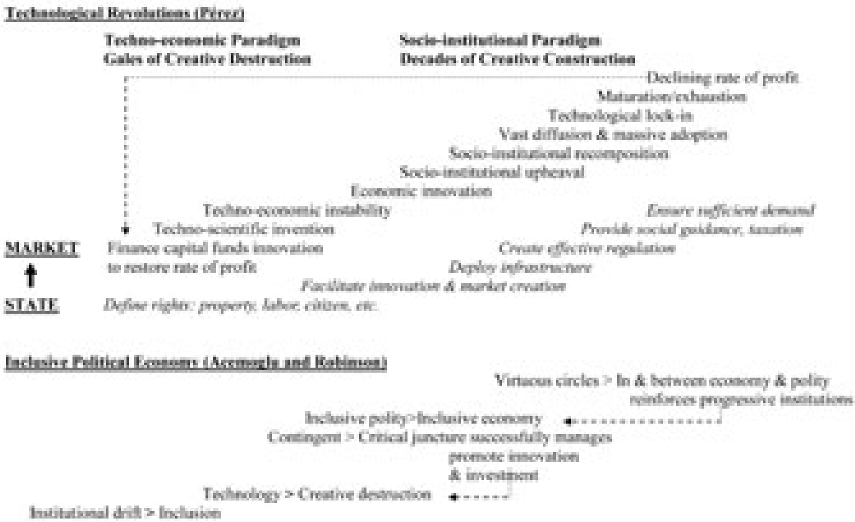


Figure 3.1 Economic Theories of Long Waves of Technological Revolution and Economic Development

Sources: Upper section of the graph based on Carlota Pérez, "Technological Revolutions, Paradigm Shifts and Socio-Institutional Change," in *Globalization, Economic Development and Inequality: An Alternative Perspective*, ed. Erik Reinert (Cheltenham, U.K.: Edward Elgar Publishing, 2004). Lower section of the graph based on Daron Acemoglu and James A. Robinson, *Why Nations Fail: The Origins of Power, Prosperity, and Poverty* (New York: Crown Publishers, 2012).

These models represent a strong vector of contemporary analysis of political economy, seeking to link economic development directly to sets of values through historical analysis. Some of these models launch from the technoeconomic side, others from the political side. However, as rigorous, non-Marxist critiques, they overlap in adopting a progressive view of capitalism in their method of historical analysis and their appreciation of the important role of politics and the state. To reflect the important shift in focus to policy and institutions, we begin with a brief discussion of the role of the state.

THE STATE AND THE TURN IN A PROGRESSIVE DIRECTION AT CRITICAL JUNCTURES

In these models, the political institutions—above all, the state—determine the context for capitalism (particularly the division of labor) by defining rights, such as property rights, contract rights, labor relations, and so on. Beyond this foundational role, the state fosters innovation by supporting important early activities, including research and development, market creation, and infrastructure deployment. It appears to become less active as the new technoeconomic paradigm spreads, but becomes active again when the bubble of development bursts, making a strong comeback through the process of institutional recomposition to create a stable path of development.

For Acemoglu and Robinson, the essential characteristic of successful nations is inclusiveness in both political and economic institutions.[3] This is an essential feature of a progressive capitalist economy where the state has the prime-mover role.[4] Political institutions establish the framework of rights necessary to ignite the success of the market, which is driven by investment and innovation. In the polity, they emphasize inclusive processes that create an environment of security. Cooperation is facilitated through the critical role of a centralized and active state establishing the necessary conditions.

> Secure property rights, the law, public services, and freedom to contract and exchange all rely on the state, the institution with the coercive capacity to impose order, prevent theft and fraud, and enforce contracts between private parties. To function well, society also needs other public services: roads and a transport network . . . a public infrastructure . . . and some type of basic regulation to prevent fraud and malfeasance.[5]

Creating regulatory institutions is one of the central activities of institutional recomposition (taxation and antitrust being the other two).[6] This period involves a significant amount of redefinition of the division of labor and redistribution of surplus to support a massive increase in support for demand. The state again appears to become less active as the institutions become routinized. The key to successfully making the transition to a stable growth path at the critical juncture has been a turn toward progressive policies of a strong state. The seeds of the next round of creative destruction and construction are being planted in the slowdown of the maturity phase, and the process is repeated.

The process exhibits strong feedback loops that sustain the path of development once the technoeconomic and socioinstitutional paradigms take hold. The outcome is not predetermined, however. There is a constant struggle to create and defend the necessary institutions, driven first by the resistance of the incumbents to creative destruction, and then by the resistance of the ascendant interests to the imposition of restraints.[7]

Both of the models rely on intense historical analysis of the development of economic systems to make their case. Pérez examines the history of capitalism through several industrial revolutions (she counts five periods defined by different dominant technologies) to extract patterns of regularities. Acemoglu and Robinson cast a wider historical net, relying on a broad concept of the development of inclusive political economies (of which capitalism is one form). Great Britain, in the period covering the institutionalization of capitalism, is by far the most frequently cited case.

The turn toward progressive policies at past critical junctures is the focal point of this analysis because we are at a critical juncture in the digital industrial revolution. Acemoglu and Robinson date the first progressive turn of the capitalist political economy to the 1820s and 1830s, long before Marx's conclusion that capitalism was doomed to extinction. They argue that Marx's laws fail

> Mostly because they ignored both the endogenous evolution of technology . . . and the role of institutions and politics that shape markets, prices and the path of technology. . . . The distribution of the gains from new technologies was also shaped by an evolving institutional equilibrium. The Industrial Revolution went hand-in-hand with major political changes.[8]

Anderson argues that the turn toward progressive policy early in the second Industrial Revolution "should be seen as developments internal to the dynamics of democratic capitalism itself,"[9] which are integral parts "of advanced capitalist democracies . . . that amount to departures from *laissez faire*." She identifies a long list of interventions that are necessary, requiring and justifying state actions that include:

1. State provision of public goods, such as roads, public health programs, and schools,
2. Centralized banking,
3. Regulation of the environment, securities markets, food and drugs, auto safety, etc.,
4. Social insurance and, to a much smaller extent, "welfare,"
5. Laws enabling labor unions (weak in the United States, but much stronger in Europe).[10]

The third progressive turn in capitalism extended the progressive-era institutions broadly with the New Deal and the post-war expansion of the welfare state.[11] The key elements are familiar now, but seemed radical at the time. As Pérez puts it:

> Saying then that the way to increase markets for automobiles, refrigerators and houses was to incorporate the great majorities (including

> the low-skilled workers) into consumption would have been deemed unrealistic. Yet it was achieved by raising wages with productivity increases and by setting up a Welfare State that subsidized mortgages; helped keep monthly payments going with unemployment insurance; covered all or part of the costs of health and education, freeing incomes for consumption, etc. Today that seems absolutely normal.[12]

The key to overcoming the resistance to regulation and direction from the state is the acceptance of the mutual benefit—the positive-sum game—of the economic development path.[13] Pérez's description of the potential for the Golden Age of the digital political economy is aspirational, but the historical analogies give it credence as a goal.[14] She portrays ICTs as a huge sink for capital investment and consumer spending, a source of economy-wide improvements in efficiency, and central to transforming the energy resources system of advanced industrial economies to sustainable renewable resources.[15] This is "just the global version of what sounded utopian in the 1930s."[16]

In the historical periodization used in this analysis, we now stand at the turning point between the periods of installation and deployment of the Information and Communications Technologies (ICT) technoeconomic paradigm, with the prospect of a golden age, if policy can create an institutional paradigm and guide the economy in a progressive direction. But the policy context is particularly complex and challenging at this moment because creative destruction has deeply affected the economy, while creative construction is just beginning at the institutional level. The change in direction and role for the economy and the state, finance and the real economy, converge. Political tensions are high.

THE MORAL FRAMEWORK

The key elements of a moral framework are deeply embedded in the above account of the economic process and history of progressive capitalism. The political economy strives to be inclusive, with the state providing entitlements that empower individuals to participate in the full range of social, economic, and political life. Inclusiveness is both a means and an end.[17]

Anderson, a student of Rawls,[18] points back to Adam Smith's discussion of what is necessary to participate fully in society.[19] She offers a theory of "Democratic Egalitarianism," based on "range constrained, property-owning democracy . . . contrasted . . . to a welfare state."[20] Progressive capitalism[21] captures the essence of the engine of progress at the center of the economy and the political institution of distributive justice that can secure its future. Anderson's comprehensive framework is defined in Table 3.4, with sources and citations for Anderson's work and the parallel formulation in the Papal Encyclical on Climate Change provided in Appendix I.

The recognition of the role of the state in creating markets is one of the central dividing lines in theories of progressive distributive justice.[22] *Laissez faire* capitalism foregoes the central virtue of capitalism as a socioeconomic system by failing

> to grasp some ways in which capitalism advanced freedom and equality. . . . Contrary to laissez faire capitalism . . . these concrete capitalist formations require limits on freedom of contract and the scope of private property rights. . . . Capitalism enabled the mass of people to see themselves as entitled to respect and dignity in their commercial relations.[23]

The active role of the state extends to the most fundamental market relations. "Property rights are artificial, *all the way down*. A primary role of the state in a market egalitarian system is to *define* a system of artificial property rights that realizes freedom and equality."[24] This takes on an increasingly important role as the economy advances.[25] The central factor is "the productive capacity to overcome mass poverty," but capitalism also unleashes a "perennial gale of creative destruction" against which only the state can provide adequate shelter.[26]

Property guarantees that inequality will play a central role in the economy, both as a dynamic force of progress and a source of severe tensions. Outcomes are "range constrained." This is not because we pity those who fail or envy those who succeed, but rather because constraints on the range of outcomes are indispensable to the proper functioning of a market-based economy and the achievement of the democratic equality that makes markets work. Market forces determine distribution outcomes, "but only within an acceptable egalitarian range."[27]

The range constraint that has been the focal point of democratic equality focuses primarily on income distribution. This carries productivity implications because without it, either members of society cannot be productive (primarily at the bottom or in the middle) or resources are wasted on unproductive activity (at the top). The need for an increasingly fine-grained division of labor does not mean it is free of constraints.[28]

The predicate for democratic equality in the economy is a "comprehensive system of joint production, [in which] workers and consumers regard themselves as collectively commissioning everyone else to perform their chosen role in the economy."[29] The primary tool for achieving interpersonal equality is a properly functioning division of labor based on the

Table 3.4 Distributive Justice in the Energy Sector: Democratic Equality and the Encyclical on Climate Change as Progressive Capitalism

Focus	Social Purpose	Income Level	Threat/ Problem	Policy Tools/ Remedies	Derivative & Complementary Effect
Democracy[1,A]	Collective self-determination by means of open discourse among equals,[5] Cooperative[6] social experimentation[9,B] Social relations of equality[10] Social basis of equal standing[11,C] Epistemic justice[14] to create institutions to foster norms[16] of communicative justice[18,D] & expand scope of prosocial norms[20,E]	All the way	Oppression[AA] Lack of Respect[AB] Reciprocation[AC] Segregation[12,AD] Disrespect, Shunning Prejudicial exclusion from meaning-making activities[19,AE]	Pure procedural justice[2,BA] & Substantive outcomes,[4,BB] Institutions for discovery Discussion, decision, voting,[7,BC] dissent[8,BD] Integration Education,[BE] Integration[15]	Humanitarian impulse,[3] Unfairness of bad luck Social basis of self respect[13] Value-based individual action[17]
Property[1,F] owning markets[29]	Individual & Collective responsibility,[25,G] Agency,[26,H] Recognize role of capital labor & firms,[34,I] Understand capitalism's dynamism,[37] progress,[40,J] & risk management[41,K]	All the way & Global[30]	Inadequate surplus[22,AF] Misallocation of risk & reward[31,AG] Market failures[35] & behavioral factors[38,AH]	Division of Labor,[23,BF] Careful[24] range constraint,[27,BG] Progress[28,] Workplace governance[32,BH] Rich opportunity set[36,BI] Proper role of state & corporations[39,BJ]	Keynesian demand sufficiency Avoid stigma and pity[33]

Equality[42,L]	Entitlements set the thresholds[43,M] to achieve Autonomy, Equal Standing, Reciprocity,[47] & Personal Independence[50,N]	Bottom	Poverty[44,AI] Subordination Insufficiency[48,AJ]	Distribution through the division of labor,[46,BK] Redistribution through the development of human capital[49,BL] & the safety net[51,BM]	Distributive fairness[45]
Independence	Ensure freedom to choose[52,O] Promote Solidarity & Community	Middle	Insecurity,[53,AK] Segregation	Social Insurance (risk pooling)[54] as an entitlement[55]	Prevent envy
Constrain Inequality[58,P]	Promote Solidarity & Community,[Q] Prevent leverage for advantage[59,R]	Top	Hierarchy,[56,AL] Segregation Avoid plutocracy[60,AM]	Taxation,[57,BN] Campaign spending limits,[BO] Integration	Promote mobility Prevent envy

See Appendix I for note references.

recognition that all labor contributes to the output of a cooperative social endeavor. Placing the division of labor at the center of economic and social institutions also makes distribution of surplus through the division of labor the first pillar on which both the economy and democratic equality stands. As the division of labor transcends national borders, the principles of democratic equality apply to all workers wherever they are located.[30] The reliance on the division of labor highlights the importance of investment in ensuring that workers have the tools to perform properly-rewarded tasks within—and the opportunity for upward mobility through—the division of labor.

The key to our argument is that the terrain of justice evolves with economic development and the social institutions that are created to support it. We emphasize three key recursive links between the economy and the system of distributive justice: the generation of surplus, the advance of the division of labor to support investment and growth, and the social state to support demand. Expansion and distribution are two sides of the same coin. They are key links in a virtuous circle of rising civilization and surplus. The creation of surplus provides the resources to expand and improve material wealth, which allows civilization to advance.

A PROGRESSIVE VIEW OF MARKET ANALYSIS

This view of the political economy of progressive capitalism fits with a long tradition of progressive economic thought known as the Structure-Conduct-Performance (SCP) paradigm. While this paradigm has been broadly used to analyze industry structure and market performance for over a century, it is particularly appropriate for the infrastructure sector. Needless to say, the energy sector has long been considered one of the core infrastructures of a political economy.

At one level, this concept of pragmatic progressive capitalism is not a particularly extreme framing of the aspiration for the political economy. In fact, it states more forcefully concepts that are at the core of the American progressive tradition. As shown in Figure 4.2, the SCP paradigm accepts the prominent role that markets play and the fact that markets may not perform well. This opens the door to an important role for policy to correct market imperfections and failures. Scherer and Ross argued that "what society wants from producers of goods and services is good performance. Good performance is multidimensional."[31]

Scherer and Ross argue that, for markets, "good performance" should entail "efficiency" and be "responsive . . . to consumer demand . . . be progressive, taking advantage of opportunities opened by science and technology to increase output . . . and to provide consumers with superior new products."[32] They should endeavor to "facilitate stable full employment of resources, especially human resources." "The distribution of income should be equitable." At the same time, they recognize that "for a variety of reasons markets may fail. . . . Then government agencies may choose to intervene and attempt to improve performance by applying policy measures that affect either market structure or conduct."[33] They argue that the first reason to choose markets is that "the atomistic structure of buyers and sellers required for competition decentralizes and disperses power."[34]

At the center of the framework (as shown in Figure 3.2) is market structure, defined primarily by the number and size of sellers. Scherer and Ross note that "Measuring the degree to which the goals have been satisfied is . . . not easy."[35] In a workably competitive market, firms are constrained by competitive market forces to earn only a "normal" rate of

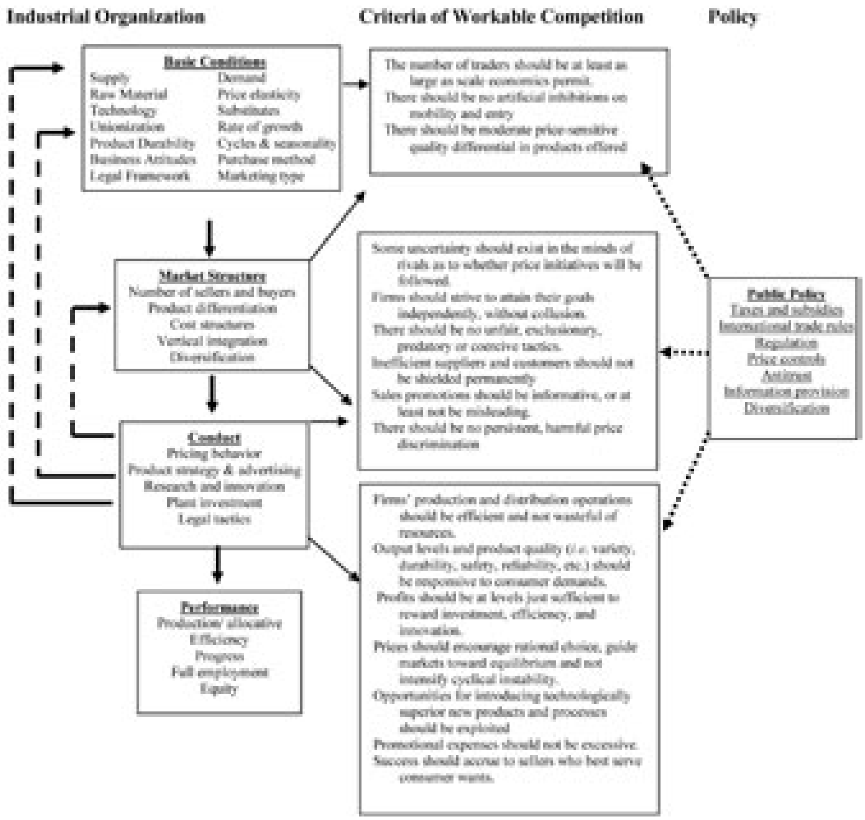


Figure 3.2 The Structure-Conduct-Performance Paradigm

Sources: Gene Kimmelman and Mark Cooper, "Antitrust and Economic Regulation: Essential and Complementary Tools to Maximize Consumer Welfare and Freedom of Expression in the Digital Age," *Harvard Law & Policy Review* 9 (2015); Frederic M. Scherer and David Ross, *Industrial Market Structure and Economic Performance* (3rd ed.; Boston, MA: Houghton Mifflin, 1990), 5, 53–54.

profit. They do not have the power to gain excess profits by setting prices unilaterally through collusion or coordination of their conduct. They are also driven to invest and innovate in order to win and hold customers who have the ability to choose which products to consume. This forces firms to be responsive to consumer needs that evolve over time.[36] However, where markets are not workably competitive, firms can set prices far above costs to obtain excess earnings, slow innovation, restrict consumer choice, and deliver inferior goods and service.

While the state can be seen in the Structure-Conduct-Performance paradigm in the basic condition of the legal framework and in policies on regulation, taxation, antitrust and information, the pragmatic progressive capitalist framework sees a larger, earlier, and more profound role for the state. Here we briefly review two well-known presentations of the paradigm—one general (Scherer and Ross),[37] and one specific (Alfred Kahn on infrastructure).[38] These brief reviews are intended not only to ground our perspective in this tradition, but more importantly to link it to the market structure analysis in Part IV and the policy responses in Part V.

Infrastructure industries are very good examples of an area of the economy where regulation has been deemed necessary. In these large and important sectors, the market structure tends to be dominated by a small number of big firms that have a significant impact on a wide range of activities.

Alfred Kahn identified these characteristics in his seminal work, *The Economics of Regulation*.[39] Making the case for economic regulation, Kahn pointed to the fact that, because infrastructure networks exhibit economies of scale, the market will support only a small number of large firms compared to other sectors of the economy.[40] In addition, because of the essential inputs they provide, they influence the growth of other sectors and the economy.[41] Kahn added two other characteristics: "natural monopoly" and "for one or another of many possible reasons, competition does not work well."[42] Although Kahn was skeptical of the monopoly rationale for regulation, he later argued that the nature and extent of competition is an empirical question:

> The question is not simply one of how much competition to allow—how much freedom of entry or independence of decision making with respect to price, investment, output, service, promotional effort, financial, and the like. It is a question also of what, in the particular circumstances of each regulated industry, is the proper definition, what are the prerequisites, of effective competition.[43]

Kahn's description of the rationale for regulating infrastructure encompasses three major economic principles. He starts with what is essentially a positive externality—a public goods argument. The broad economic impact means that private individuals might not see the benefits, or might be unable to appropriate (capture) that value in the form of profits, so they will invest less in the provision of service than is socially justified. In addition to this macroeconomic impact, those who are unserved or priced out of the market are disadvantaged at the individual level.

An extension of this for the infrastructure network involves achieving ubiquitous, seamless interconnection and interoperability, which is not a likely outcome of market forces alone.[44] Ubiquitous, seamless interconnection and interoperability are a highly desirable characteristic of infrastructure networks that achieve important network effects—another positive externality.

The second rationale offered by Kahn is a market structure problem. Very large economies of scale mean that building multiple networks raises costs. The market will not support competition. In the extreme, we run into the problem of a natural monopoly. Monopolists (natural or otherwise) have market power, and there is a strong incentive to abuse it. Firms that become too large behind high barriers to entry, or transaction costs on the supply-side, or high switching costs, or other behavioral flaws on the demand side, will obtain market power. With the incentive and ability to exercise it, they engage in behaviors that harm competition (by creating additional obstacles to entry or extending their market power to complementary markets) and consumers (by raising prices and restricting choices). Regulation controls market power. However, monopoly is not the only reason to implement public policy—for example, it has never been a necessary condition to common carriage in the communications and transportation sectors.

Infrastructure industries exhibit a number of market structural problems. They deliver service with relatively low elasticities. In fact, they can be considered "necessities" since they have a combination of low price elasticity and moderate income elasticity.[45] The low price elasticity means it is difficult to go without the service or find good substitutes. The moderate income elasticity means the good commands a significant part of the household budget all across the income distribution, but the percentage declines as income rises. The important role of infrastructure for the household and in the broader economy magnifies the ability to abuse market power, as well as the impact of those abuses.[46]

Finally, we have Kahn's third reason for regulation—"other." Although it is less specific, it can be given several particular referents in the energy sector. Competitive markets do not deliver universal service because there are significant parts of society where the rate of profit does not support extending the infrastructure or making it affordable. Rural/high cost areas and low income population may not be very attractive from an investment point of view, but they are important from a public policy/social values point of view.

These very fundamental economic and noneconomic justifications for public policy to promote ubiquitous, affordable infrastructure services are frequently reinforced (and preceded) by the rationale that much infrastructure relies on some form of public license—use of rights of way, control of airwaves, grants of authority like exclusive franchises, and eminent domain. Those rationales are important and they tend to be stated first because they are easy and obvious. However, the broader factors are at least as important.

Therefore, infrastructure sectors provide a fertile ground for the abuse of market power. Their size, great importance to the functioning of the economy, and underlying economic characteristics suggest that the existence and persistence of market power is a particular problem. This has made infrastructure sectors the target of a great deal of public policy.[47] Elasticities of demand and supply are low compared to other sectors. Deployment of facilities to compete with an incumbent communications network is costly and difficult. Network effects, the ability to reach large numbers of customers to make the network more valuable to each individual customer, are important.

This analytic framework underscores the fact that studying market performance is an empirical undertaking. One must assess the performance of real markets and identify any imperfections that diminish its performance. This is the approach taken in Part IV, where imperfections in energy markets are viewed through two lenses—the efficiency gap and climate change. Having identified the causes of market failure, the practice of political economy requires further analysis to identify the specific policies that are best able—most effective and least-cost—to address the underlying problem, which is presented in Part V.

In adopting the welfare economic and industrial organization frameworks, we take the position that they are useful tools for economic analysis as long as they are embedded in and constrained by a broader analytic framework of political economy, like progressive capitalism. This discipline on the analytic tools is fully cognizant of the strong critiques of their underlying assumptions and uses those critiques to negate the distortions that their erroneous assumptions can introduce.

CONCLUSION: THE PAPAL ENCYCLICAL ON CLIMATE CHANGE

In Chapter 9, we point to pieces by prominent economic columnists in two well-respected general audience publications (the *New York Times* and *The Economist*), arguing that the literature on climate change has broken through to a broader, nonpolicy, nonacademic audience. An even more compelling piece of evidence—and more important contribution to the discussion—is the Papal Encyclical on Climate Change, *Laudato Si'*, which reinforces the moral framework discussed above.[48] Although one can point to a steady stream of progressive Papal Encyclicals, like the need to ensure fair treatment of labor[49] and concerns about the poor and powerless, *Laudato Si'* triggered an intense reaction, as if its principles were a bolt of lightning. It was attacked by free-market climate deniers and anti-market (even Marxist) analysts[50] and it was criticized by economists supporting climate policy as insufficiently appreciative of the role of markets and technology.[51] Even before the Papal visit to Washington, it was widely recognized as an extremely important development in the global debate over climate change and energy poverty.[52]

Notwithstanding the strong reactions, when placed in historical context, the document fits neatly not only in longstanding positions of the Catholic Church, but also in the current stage of development of economic thinking. The idea of a living wage was first expressed in a 1891 encyclical, during a period that is labeled in the United States as the Progressive Era. It was also in this period that social security was adopted in Prussia, and European socialists abandoned class warfare as the driving force for economic change.[53] At key moments over the past century, this progressive view has been reiterated—in 1931, at the onset of the Great Depression; and in 1981, the eve of the Reagan Revolution.[54] *Laudato Si'* is squarely in that tradition and, we argue, in the progressive framing of political economy outlined in this book.

Laudato Si' bridges the universes of the pastor and the scholar, consistent with Pope Francis' Jesuit background. It recognizes the importance of technology and markets, and reconciles the complementary roles of the scientific and religious world views by insisting that science, technology, and markets should be embraced, but only when they are guided by social values—one of the most important being the commitment to promoting social justice. It contains all three ingredients of a political economy. Appendix I shows how closely its theory of justice fits with democratic egalitarianism. Here I highlight the three legs on which a political economy must stand:

First, the importance and limitations of markets:

> The environment is one of those goods that cannot be adequately safeguarded or promoted by market forces. . . . Efforts to promote a sustainable use of natural resources are not a waste of money, but rather an investment capable of providing other economic benefits

> in the medium term. If we look at the larger picture, we can see that more diversified and innovative forms of production which impact less on the environment can prove very profitable. Yet by itself the market cannot guarantee integral human development and social inclusion.[55]

Second, a moral framework:

> We have the freedom needed to limit and direct technology; we can put it at the service of another type of progress, one which is healthier, more human, more social, more integral. Underlying the principle of the common good is respect for the human person as such, endowed with basic and inalienable rights ordered to his or her integral development. It has also to do with the overall welfare of society and the development of a variety of intermediate groups, applying the principle of subsidiarity. A technological and economic development which does not leave in its wake a better world and an integrally higher quality of life cannot be considered progress. Postmodern humanity has not yet achieved a new self-awareness capable of offering guidance and direction.[56]

Third, a political mechanism:

> The establishment of a legal framework which can set clear boundaries and ensure the protection of ecosystems has become indispensable, otherwise the new power structures based on the technoeconomic paradigm may overwhelm not only our politics but also freedom and justice. The myopia of power politics delays the inclusion of a far-sighted environmental agenda within the overall agenda of governments. Let us keep in mind the principle of subsidiarity, which grants freedom to develop the capabilities present at every level of society, while also demanding a greater sense of responsibility for the common good from those who wield greater power. But economics without politics cannot be justified, since this would make it impossible to favour other ways of handling the various aspects of the present crisis.[57]

The fact that Pope Francis hails from Buenos Aires is coincidental but instructive. It is not clear how much the Papal Encyclical mattered in 2015, but judging by the reaction of the American *laissez faire* climate deniers to Pope Francis' U.S. visit, as well as their effort to prevent agreement in Paris, it could not have hurt.

4

THE INNOVATION SYSTEM OF PROGRESSIVE CAPITALISM

INTRODUCTION

At the heart of the economic engine of the capitalist industrial political economy is an innovation system. The study of innovation has blossomed in the past several decades as its impact on the speed and direction of economic growth has been acknowledged. As development and growth have persisted, becoming deeply embedded aspirations in society, and as the economy has become more complex and interconnected, the desire and ability to influence innovation has grown. From the residual in the estimation of production functions, it has become the centerpiece of analysis and policy.

The recognition of a process of innovation and entrepreneurship that drives a virtuous cycle of investment and growth has become central to the discussion of the digital political economy. The virtuous cycle framework posits that innovation and investment at the edge of the network is inextricably linked to innovation and investment in the network itself in a recursive, reinforcing feedback loop. Development of applications, devices, and content stimulates demand, driving innovation and investment in the supply of infrastructure network capacity and functionality. In turn, improving network functionalities and expanding capacity make new applications possible, which stimulates new demand and allows the cycle to repeat.

This section brings to bear two of the most prominent insights on the issue of the virtuous cycles that are central to the innovation system and the digital technical-economic paradigm. First, we discuss the broad field of innovation-diffusion analysis. Then we introduce innovation system analysis, which provides the opportunity to create a strong link to policy.[1] Finally, we show several direct applications of the framework to the energy sector.

INNOVATION AND DIFFUSION

The innovation diffusion process has typically been represented as a logistic (S) curve that represents the overall flow of product development and adoption actions (see Figure 4.1).[2] Economic analysis of the diffusion of products has shifted focus between the supply side and the demand side of the market several times over the past century. The pre-World War II focus was on "invention and innovation" (consistent with a Schumpeterian focus), but the three decades after the war focused much more on the demand side (consistent with the Keynesian tenor of the times). In fact, by

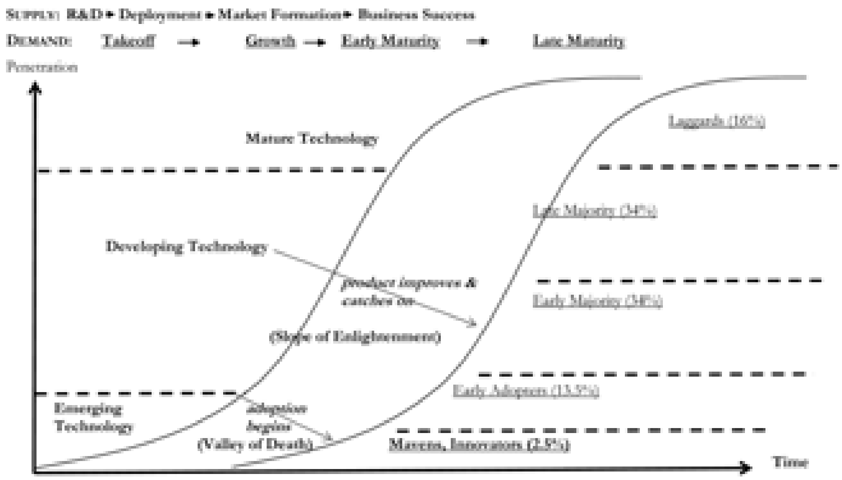


Figure 4.1 The Interaction of Supply and Demand in the Creation/Diffusion of Innovative Technologies

Sources: Vijay Mahajan, Eitan Muller, and Frank M. Bass, "New Product Diffusion Models in Marketing: A Review and Directions of Research," *Journal of Marketing* 54 (1990); Peter N. Gilder and Gerard J. Tellis, "Will It Ever Fly? Modeling the Takeoff of Really New Consumer Durables," *Marketing Science* 16 (1997); Erik Jan Hultik et al., "Launch Decision and New Product Success: An Empirical Comparison of Consumer and Industrial Products," *Journal of Product Innovation Management* 17 (2000); Bing Jing, "Social Learning and Dynamic Pricing of Durable Goods," *Marketing Science* 30 (2011); Ashish Sood et al., "Predicting the Path of Technological Innovation: SAW vs. Moore, Bass, Gompertz and Kryder," *Marketing Science* 31 (2012).

the 1990s, the field was criticized for ignoring the importance of the supply side. Focus is once again on a balance of the two.[3]

The two key challenges that affect the flow of the process are technology selection (predominantly a supply-side issue) and technology adoption (a demand-side issue). Six sets of factors are seen to influence the outcome of these two tasks. The dominant factors that affect both technology selection and diffusion are technology and user characteristics and social context. The earlier discussion of the virtuous cycle identified factors in each of the six areas that triggered the powerful innovation cycle of the Internet.

On the supply side, the process moves through a number of phases. In the first phase, technology incubates and emerges from research and development ready to be launched. The early supply-side period is very challenging and has been called a "valley of death" that must be traversed if the product is to advance.[4] The product undergoes continuous development as it is commercialized and succeeds (a process that has been called the "slope of enlightenment").[5] The product stabilizes as it matures and then saturates the market. Saturation may not be at 100 percent since some parts of the market may never adopt a product for a variety of reasons.

The challenge of diffusion is first and foremost a matter of supply-side innovation. To put the matter simply, consumers cannot adopt technologies until they are offered in the marketplace. Innovation must precede diffusion.[6] Recognition of the importance of the supply side also reflects a greater emphasis on the role of entrepreneurship and management in the innovation process because "takeoff is not instantaneous and requires patience and careful planning on the part of managers."[7] Management faces a variety of challenges in shepherding innovative technologies to business success.[8]

Management can have different motives for technology innovation and use different tools to increase the likelihood that the technology will achieve a large enough market to be profitable.[9] Entrepreneurs make the decisions about what technologies to develop and products to market, as well as how those products are priced, brought to market, and promoted. They do so in response to their perception of the market they are located in, their understanding of consumers, and their own preferences. Their ability to perform these activities is neither perfect nor uniform.[10]

Of course, the demand side is important, too. On the demand side, the process begins with initial adoption by market mavens and innovators, then spreads through early adopters, early and late majorities, and finally laggards. The adoption process accelerates rapidly with takeoff, then slows with maturity. The speed and ultimate level of adoption have been primary focal points of analysis on the demand side.

The assumption on the demand side is that the underlying process "is a social learning process which results in consumers slowly changing their attitudes and values . . . some individuals change their views quicker than others; it is a 'rolling snowball' phenomenon which starts with just a few people and gets bigger as it gathers momentum."[11] The demand-side approach looks both at the aggregate level of penetration and the individual adoption decisions.[12]

The literature identifies four broad categories of factors that affect adoption on the demand side: demographics, social influences, attitudes, and the ability to make calculations. Because of its focus on the consumer adoption decision, the diffusion literature is very sensitive to causal factors that drive diffusion—factors that are grounded in behavioral economics, including: *Perception*: Type of Uncertainty, Uncertainty Model, *Preference Structure*: Attributes, Risk Attitude, Adoption, *Decision Rules*: Maximize Expected Utility, and *Learning*: Model, Sources of Information.[13]

CRITIQUE OF THE *LAISSEZ FAIRE* MODEL

The field of innovation diffusion analysis has grappled with exactly the same issues that we see in the broad critique of the neoclassical *laissez faire* market fundamentalist framework. A major source of tension in the innovation diffusion field flows from the approach to modeling behavior and process—the efficient market hypothesis underlying neoclassical economics versus the institutional, transactional, and behavioral economics views of imperfect markets.

> The issue relates to whether the diffusion process should be formalized as [*neoclassical equilibrium*] . . . with diffusion patterns reflecting a sequence of shifting equilibria over time in which agents are fully adjusted . . . modeled as being infinitely rational and fully informed . . . or as a disequilibrium process . . . modeled as being constrained by lack of information or understanding on the part of adopters about the worth of an innovation.[14]

As noted above, and shown in Table 4.2, the neoclassical *laissez faire* model has been contested at every level for the fundamental failure of its explanations and predictions. The alternative arguments provide the building blocks for major alternative schools of thought that have been recognized in a series of Nobel Prizes over the past quarter of a century. These critical schools of thought expand and strengthen the market failure analysis described in Part IV. Table 4.1 locates each of these schools of thought within the framework of the structure-conduct-performance paradigm that dominated in the United States during periods of progressive policy. It shows the general correspondence of the critiques to the differences in fundamental economic models used to describe the workings of the economy.

The broad critique of the neoclassical economic model that echoes in the efficiency gap debate discussed in Chaper 7 rested primarily on the fact that the underlying assumptions of infinitely rational/fully informed actors in the neoclassical model does not fit real world behaviors at all.

> As Simon stressed in his Nobel Memorial Lecture, the classical model of rationality requires knowledge of all the relevant alternatives, their consequences and the probabilities, and a predictable world without surprises. These conditions, however, are rarely met for problems that individuals and organizations face. Savage, known as the founder of modern Bayesian decision theory, called such perfect knowledge small worlds. . . . In large worlds, part of the relevant information is unknown or has to be estimated from small samples, so that the conditions for rational decision theory are not met, making it an inappropriate norm for optimal reasoning. In a large world . . . one can no longer assume that "rational" models automatically provide the correct answer.[15]

The effort to understand the complex influences on human behavior has moved well beyond the simple "rational v. irrational" dichotomy.[16] The middle ground recognizes that "intelligent choice," "useful inferences," and "smart" decisions are possible without reference to "the classic model of rationality."[17] *Ecological rationality* is a term applied to this middle ground that recognizes the limitations imposed on choice by the environment and the capacity of individuals to make decisions.

> The study of ecological rationality is related to the view that human cognition is adapted to its past environment.[18]
>
> In a complex and uncertain world, humans draw inferences and make decisions under the constraints of limited knowledge, resources, and time. . . . These heuristics perform well because they are ecologically rational: they explore the structure of environmental information and are adapted to this structure.
>
> Models of ecological rationality describe the structure and representation of information in actual environments and their match with mental strategies, such as bounded rational heuristics. The simultaneous focus on the mind and its environment, past and present, put research on decision making under uncertainty into an evolutionary and ecological framework, a framework that is missing in most theories of reasoning, both descriptive and normative.[19]

Table 4.1 Market Fundamentalism Versus Progressive Capitalism

Fundamental Differences and Practical Implications		
Model Assumptions	**Market Fundamentalism**	**Progressive Capitalism**
Units of Analysis	Closed system Individual Utility as an end Risk	Open system due to unpredictability & choice Institution as means and ends Capabilities as means and ends Uncertainty (Keynesian/Knightian)
Individual Actors	Individual utility maximizers Infinite rationality Full/unlimited information	Socially grounded satisficers Bounded rationality Necessarily limited-information
Market Process	Markets are efficient Government is part of the problem Diffusion ahistorical & Efficient Continuous & Quantitative Equilibrium mechanism Predictable Mechanistic laws Static	Market failure is substantial and pervasive Government provides solutions Social policy as means and end for development Path-dependent (historicity) Possible significant inefficiency Discontinuous & qualitative (non-Darwinian) Disequilibrium mechanism Unpredictable Interconnected systems Dynamic
Welfare Economics & Policy	Wealth = utility Uniform marginal value of wealth Total social surplus is all that matters Inequality does not matter, in fact more is better to squeeze surplus out of labor	Well-being = capabilities Declining marginal value of wealth Distribution of surplus matters between producers and consumers among consumers Excessive inequality is harmful: raise the floor support a refined division of labor sufficiency at the bottom, security & mobility in the middle, constraint at the top

Universal Service	Willingness to pay Static view of benefits Complexity is a challenge that cannot be dealt with Access anywhere is sufficient 80% penetration is okay Barebones functionality is what you get	Ability to pay Dynamic view of benefits Complexity as an indicator of the immense value of access indicates we must solve the problem Access at home is vital to full participation 95% penetration has been the standard of 20th-century infrastructure Full functionality is what we need

New School of Thought Enriching the Understanding of Market Imperfections

S-C-P Factor	New School of Thought
Basic Conditions:,	**New Institutional/Transaction Cost Economics:** Ronald Coase, 1992; Douglas North, 1993; Robert Fogel, 1993; Oliver Williamson 2009; Elizabeth Ostrom, 2009 **Endemic Flaws:** Joseph Stiglitz, 2001; Michael Spence, 2001
Market Structure	**Deeper Critique of Structural Imperfections:** Paul Krugman, 2008; Jean Tirole 2014; James Heckman, 2008; Angus Deaton, 2015
Conduct:	**Behavioral Economics:** George Akerloff, 2001; Daniel Kahneman, 2002; Vernon Smith, 2002; Robert Shiller, 2013
Performance:	**End of Value Free Economics, Return of Political Economy:** Amartya Sen, 1998 Aland l of the above

Source: Jayati Sarkar, "Technological Diffusion: Alternative Theories and Historical Evidence," *Journal of Economic Surveys* 12 (1998), presents a review focused on diffusion theory. For the broader comparison, a number of sources are important: Nuno Ornelas Martins, "The Place of the Capability Approach within Sustainability Economics," *Ecological Economics* 95 (2013); Nuno Ornelas Martins, "Sen's Capability Approach and Post Keynesianism: Similarities, Distinctions, and the Cambridge Tradition," *Journal of Post Keynesian Economics* 31 (2009); Tony Lawson, "The Current Economic Crisis: Its Nature and the Course of Academic Economics," *Cambridge Journal of Economics* 33 (2009); David Singh Grewal and Jedediah Purdy, "Introduction: Law and Neoliberalism," *Law and Contemporary Problems* 77 (2014); John Gowdy, "Contemporary Welfare Economics and Ecological Economics Valuation and Policy," *Internet Encyclopaedia of Ecological Economics*, International Society for Ecological Economics, February, 2003; Geoffrey M. Hodgson, "Institutional Economics into the Twenty-First Century," *Studi e Note di Economia* 14 (2009); Geoffrey M. Hodgson, "Evolutionary and Institutional Economics as the New Mainstream?" *Evolutionary and Institutional Economics Review* 4 (2007): 4; David Dequech, "Neoclassical, Mainstream, Orthodox and Heterodox Economics," *Journal of Post Keynesian Economics*, 30 (2007): 30. Nobel Laureate lectures can be found at: http://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/.

If the baseline assumption of infinite rationality and full information is as far from reality as this discussion suggests, it is reasonable to argue that the baseline should shift to a set of assumptions that are closer to reality. This would make it more likely that the model will avoid the error of assuming that a little more information fed into a context where the underlying forces are almost right will solve the problem.[20]

Recognizing the environmental and cognitive constraints on decision making shifts the focal point of the analysis to internal criteria of performance. The focus of study shifts to the origin and impact of constraints on decision making and the tools humans use to make decisions under those constraints.

> Within ecological rationality it is of utmost importance to look at how the environment influences the tasks and how the environment shapes and has shaped the cognitive capacity of social actors. Humans have an evolutionary past in which they constantly learned and adapted to biological and social environment and this shaped their cognitive capacities. . . . In addition, humans are not error free and, even more importantly; they face a wide range of tasks in a modern technological environment.[21]

NATIONAL INNOVATION SYSTEMS AND THE STATE

One approach to the study of innovation that has received a lot of attention is the analysis of innovation systems, which takes an institutional and evolutionary view of technological change.[22] The Innovation Systems approach defines the system as a series of interrelated functions that determine the speed and nature of innovation (see Figure 4.2). Entrepreneurial activity (experimentation) is at the center of the system, with eight linkages (shown as solid arrows). Knowledge creation, which has four linkages, is the next most important node in the system.

Virtuous cycles play a prominent role in the analysis, with feedback loops reinforcing the process once it gets going. There are three important motors or triggers of innovation systems that are identified that then interact with other elements of the system—guidance of research; demands for better economic conditions to overcome inertia and make technology development more attractive; and market formation activities.[23]

The opportunity for policy to impact and accelerate the innovation process is clear in these triggers. Figure 4.2 identifies the specific policies (shown as dashed arrows) that have driven the innovation cycle that

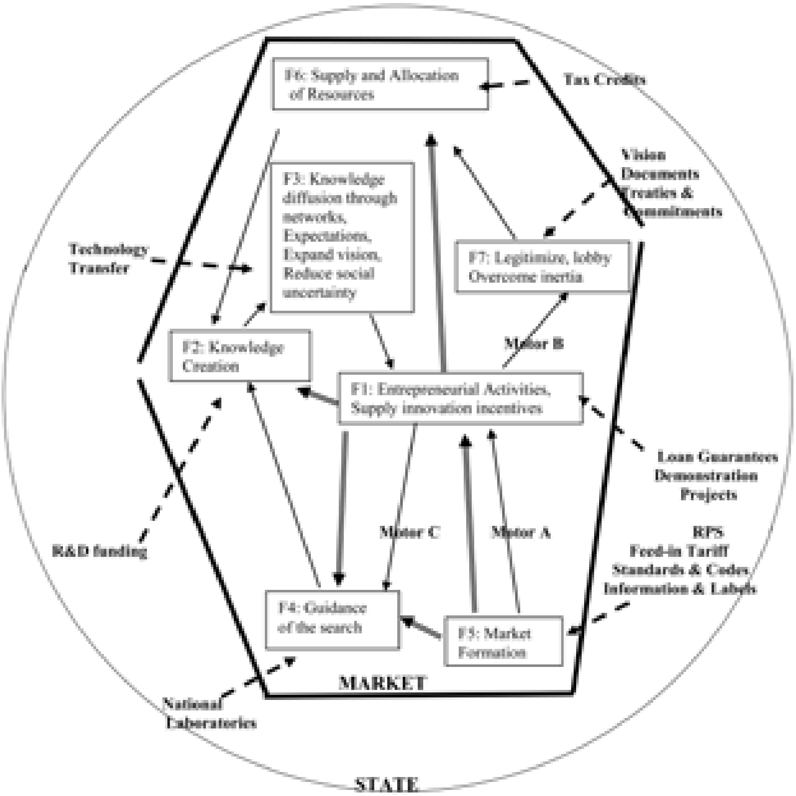


Figure 4.2 Functions and Motors in the Innovation System

Sources: Innovation system adapted from M. P. Hekkert et al., “Functions of Innovation Systems: A New Approach for Analyzing Technological Change,” *Technological Forecasting & Social Change* 4 (2007): 426 for solid arrows and motors. Anna Bergek, et al., “Analyzing the Functional Dynamics of Technological Innovation Systems: A Scheme of Analysis,” *Research Policy* 37 (2008), compound arrows.

produced the dramatic cost decreases in renewable energy technologies discussed in Chapter 1.

This process has been studied most intensely in recent years in the ICT space, but the broad framework applies to electricity. While some see discrete steps, with supply leading and demand following, there is strong evidence that the two are linked in a recursive loop through bidirectionality,[24] resulting in a very high social return on investment in these technologies.[25]

There is a feedback hypothesis (FBH) which suggests that economic growth and infrastructure can complement and reinforce each other, making economic growth and infrastructure mutually causal. The argument in favor of the bidirectional causality is that telecommunications infrastructure is indispensable to economic growth and economic growth inevitably requires a solid infrastructure in the economy.

DIGITAL TECHNOLOGY, DECARBONIZATION, AND DEVELOPMENT

The policy context is particularly complex and challenging at this moment because creative destruction has deeply and rapidly affected the economy, while creative construction is just beginning at the institutional level. Many of the practices involved in the ICT paradigm are gradually becoming accepted and commonplace to the point of being regarded as obvious organizational "common sense." Decentralized networks with a guiding center are replacing closed, centralized control pyramids. Continuous improvement and innovation is replacing the previous practice of stable routines and planned change. The notions of human capital and the value-creating powers of knowledge and expertise are displacing the view of personnel as "human resources." Although there is still resistance to some of those shifts, none has been more subject to debate and extreme positions than the shift towards globalization.[26]

The technological revolution briefly described above drives change along two mutually-reinforcing vectors. The first is innovation and investment in the ability to harness low-carbon resources to generate electricity. The second is the ability to manage the electricity system in a much more dynamic way. The tools of decentralization, coordination, and control that are at the core of the digital political economy have a direct and beneficial application to the electricity sector. The logic of the core technology applies, to varying degrees, across the economy.

The stark contrast between the emerging 21st-century digital political economy and the 20th-century political economy described by Pérez underscores this process in several ways.[27] First, the mass market production of the 20th century was very much driven by fossil fuel consumption. The digital political economy is much more dependent on electricity, which can move away from fossil fuels. Second, technologies are emerging to power more and more activity with electricity. Third, the heterogeneity of products creates niche markets. Fourth, the new division of labor is much more global and complex, shifting a great deal of activity and autonomy to users and producers on the edge of the networks.

The virtuous cycles of economic progress are interconnected in the sense that they tend to produce the key ingredients to solve the next great challenge that faces the economic system. Pérez builds this into her model of capitalism by linking Schumpeter's concept of creative destruction to the equally powerful process of creative construction. The result is a spiral of development.

Throughout human history, the ability to communicate over long distances was dictated by the ability to transport information physically. That began to change with electrification of communications; but globally, electronic communications (wireline telephone service) never penetrated beyond 20 percent in a century-and-a-quarter. Digital communications have dramatically altered the relationship between communication and physical movement. Digital mobile has penetrated to 70 percent in a quarter-century. Moreover, digital communications are increasingly becoming the means of commerce, dramatically reducing the need for physical. The ultimate goal is not only to describe the phases of technological revolutions, but also—and more importantly—to identify the causal forces that drive the evolution through repeated cycles.[28] Without a theoretical framework that understands the complex development of the technoeconomic paradigm and the division of labor, the nature of the problem is misunderstood and it is difficult to design policies to respond to the challenges that present themselves at turning points/critical junctures."[29] Of course, as noted above, decarbonization will drive the electrification of the transportation sector, and as Jacobson et al. notes, electricity uses energy much more efficiently than the fossil fuel-based technologies it is replacing.

Industrial revolutions produce the ingredients necessary to solve the challenges they face. This is certainly true of the digital industrial revolution in the energy sector, specifically the electricity sector. Dynamic technological development has produced the tools for a transformation of the energy sector that can solve the problem of climate change, while dealing with the challenge of energy justice. The model of base-load facilities, combined with fossil-powered peaking power and massive amounts of pollution (including greenhouse gas emissions), has been undercut by the dramatically declining cost for distributed renewables and storage. Rather than build fossil fuel-powered peakers that follow load, the ICT revolution has made it possible to integrate and manage demand and supply. Thanks to dramatic innovation and competition, economic analyses of the cost of addressing energy justice offered a decade ago (as it became a topic of increasing attention) are obsolete.[30] An electricity sector centered on smaller-scale, more flexible resources should facilitate and lower the cost of addressing both development and climate change. This technological revolution not only delivers affordable electricity, but it also does so in a manner that utilizes local resources and fosters local autonomy.

There is no doubt that ICT qualify as a technoeconomic paradigm whose characteristics are consistent with the description of the virtuous cycle of the Internet provided in the previous section.

> All this economic and social effort becomes a set of externalities for further investment and wealth creation based on market expansion and compatible innovations. Thus there is a virtuous cycle of self-reinforcement for the widest possible use and diffusion of the available potential. There are two areas, though, where cost reduction innovations are crucial for the growth of the whole economy: the core inputs and the infrastructure. If these are cheaper and better, more and more producers will use them to modernize their products and processes and to increase their own markets. A virtuous cycle ensues, as this growth in demand will in turn facilitate further gains in productivity in the inputs and the infrastructure themselves.[31]

The contrast between the mode of production based on information and communications technologies and the mass market technologies of the 20th century is summarized in Table 4.2.

> The digital mode of production is based on a powerful cluster of interdependent new and dynamic industries and infrastructures. These result in explosive growth and structural change . . . new multipurpose technologies, infrastructures and organisational principles that are capable of modernising all the existing industries, transforming the opportunity space and the ways of living, working and communicating.[32]

The ICT technology is firmly installed as a general purpose technology whose possibilities for application are widely seen as numerous and diverse. "The ICT revolution is now entering the deployment period, as its power to increase productivity and facilitate innovation spreads to all other industries."[33] The whole process involves a massive change in the overall direction of innovation and investment, transforming the opportunity space and ways of living, corking and communicating."[34]

Pérez has identified a number of key factors that are affected by/must be altered in the transition from the installation to the deployment phase.

> Many of the practices involved in the ICT paradigm are gradually becoming accepted and commonplace to the point of being regarded as obvious organizational "common sense." Decentralized networks with a guiding centre are replacing closed, centralized control

Table 4.2 The Second and Third Industrial Revolutions in Detail

20th Century Age of Mass Production	21st Century Age of Information/ Telecommunication
Macro-Level Paradigms	
Techno-Economic	
Mass production/mass markets	Segmentation of markets/proliferation of niches
Economies of scale (product and market volume)	Economies of scope and specialization combined with scale
Standardization of production	Heterogeneity, diversity, adaptability
Mass standardization	Componentization, Hyper-segmentation
Energy intensity, Synthetic materials	Information intensity, Microelectronic-based ICT
Socio-Institutional	
Horizontal integration	Inward and outward cooperation and clusters
Functional specialization	Decentralized integration
Hierarchical pyramids	Network structures
National powers, World agreements/ confrontations	Globalization/interaction between the global and the local
Centralized/metropolitan centers-suburbanization	Instantaneous global contact and action and communications
Micro-Level Productive Organization	
Internal Structure	
Command and Control	
Centralized command	Central goal-setting and coordination
Vertical control	Local autonomy/Horizontal self-control
Cascade of supervisory levels	Self-assessing/self-improving units
Management knows best	Participatory decision making
Structure and Growth	
Stable routine, Planned change	Continuous innovation
Clear vertical links	Interactive, cooperative links between functions, along each product line
Separate, specialized functional department	
Style of Operation	
Optimized smooth running organization	Continuous Learning and improvement
Standardized routines and procedures	Flexible system/adaptable procedures
"There is one best way"	"A better way can always be found"
Definition of individual tasks	Definition of group tasks
Single top-down line of command	Widespread delegation of decision making
Single bottom-up information flow	Multiple horizontal and vertical flows

(*Continued*)

Table 4.2 (Continued)

20th Century Age of Mass Production	21st Century Age of Information/ Telecommunication
Equipment and Investment	
Dedicated equipment One optimum plant size for each product Each plant anticipates demand growth Strive for economies of scale for mass production	Adaptable/programmable/flexible equipment Many efficient sizes/optimum relative Organic growth closely following demand Choice or combination of economics of scale, scope, and specialization
Production Programming	
Keep production rhythm; use inventory to accommodate variation in demand Produce for stock Shed labor I slack	Adapt rhythm to variation in demand Minimize response time ("just in time") Use slack for maintenance and training
Productivity Measurement	
A specific measure for each department Percent tolerance on quality and rejects	Total productivity measured along the whole chain for each product line Strive for zero defects and zero rejects
External Relations	
Personnel & Training	
Labor as variable cost, human resource Market provides trained personnel People to fit the fixed post Discipline as main quality Single function specialization	Human capital Much in-house training and retraining Variable posts/adaptable people Initiative/collaboration, motivation Multi-skilled personnel/*ad hoc* teams
Suppliers, Clients, & Competitors	
Separation from outside world Foster price competition among suppliers Standard products for mass customers Arms'-length oligopoly with competitors The firm as a closed system	Strong interaction with outside world Collaborative links with suppliers and customer and some competitors Collaborate with some competitors (e.g., R&D) The firm as an open system

Source: Carlota Pérez, *Technological Revolutions and Techno-Economic Paradigms*, Working Papers in Technology Governance and Economic Dynamics, January 2009, 18.

pyramids; continuous improvement and innovation are replacing the previous practice of stable routines and planned change; the notions of human capital and of the value-creating powers of knowledge and expertise are displacing the view of personnel as "human resources." Although there is still resistance to some of

> those shifts, none has been more subject to debate and extreme positions than the shift towards globalization.[35]

It is important to point out that the transformation of the economy also has a pervasive impact on the sociocultural dimension of society. A lifestyle that utilizes the output that the economy is best able to produce and is consistent with the relations of production develops and spreads through society. Each mode of production is associated with a very different lifestyle—the austere Victorian, the cosmopolitan Belle Époque, and the comfortable American way of life. She argues that the technologies of the first two industrial revolutions provided a progression from reading newspapers and novels, to photography, movies, and television and radio. The third industrial revolution marks an even larger change, from passive to active that reinforces the significant sociocultural shift to centering society on user-driven and creative activities.

The virtuous cycle is the micro-level base of the political economy. It is embedded in an innovation system, which is in turn embedded in a technoeconomic paradigm. These three spheres are held together and given coherence by the socioinstitutional paradigm. As Pérez puts it:

> Technology is the fuel of the capitalist engine . . . technical change has only little to do with scientific and technological reasons. It is the mode of absorption and assimilation of *innovations* in the economic and social spheres that requires technical change to occur in coherent and interrelated constellations. . . . The institutional sphere is the seat of politics, ideology and of the general mental maps of society. . . . It is also the network of norms, laws, regulations, supervisory entities and the whole structure responsible for social governance.[36]

The innovation system of the core digital sectors of the economy is the paradigm that drives change in the emerging political economy. Not every sector can achieve the same level and force of the virtuous cycle, but its principles push every sector to emulate it as far as possible.

The process of entrepreneurial experimentation is at the core of the virtuous cycles that developed in several digital technologies. While we frequently hear about positive systemic externalities that provide the powerful economic forces to reinforce the "virtuous cycles" (e.g., spillovers, network effects, feedback loops, etc.), it is important to distinguish the micro-level activities in which individuals and firms engage from the unintended macro- or system-level benefits to which they give rise.[37] Microlevel behavior is the key pillar on which the political economy rests, reflecting the incentive and motivational structure that influences behavior by making resources and opportunities available. At the micro level, we can identify a number of unique conditions associated with the digital revolution that created an extremely friendly space for the entrepreneurial experimentation.

User needs were not only much more strongly signaled, but users also became active in innovating directly and indirectly.[38] In the array of potential sources of information opened up by the digital revolution, the new paradigm provides the opportunity for the most edgy of all actors—consumers and users—to play a much larger role in driving innovation. "Of all the sources of ideas for new R&D projects outside the R&D lab itself, including suppliers, rivals, university and government labs or even a firm's own manufacturing operations, customers are far and away the most important."[39] With easy communications and transactions around open protocols and interfaces, complementary inputs created platforms where many providers could specialize and collaborate to increase output and lower cost. The arrangement resulted in a dramatic reduction in transaction costs that created a powerful network effect.

Together, those two features enabled enormous combinations of users and suppliers of data that previously would have required bilateral—and, therefore, prohibitively costly—agreements to arrange. In brief, it enabled a network effect where none had previously existed, involving participants who could not have previously considered it viable to participate in such a network.[40]

Thus, the virtuous cycle draws on a technical-economic paradigm and the institutional structure that supports it. The technical-economic paradigm thrives on entrepreneurial experimentation, while the institutional structure is based on a variety of planned and unplanned collaborative undertakings (platforms, standards, open protocols, an ecology of outsourcing components). The collaborative undertakings involve actions that are intended to facilitate the entrepreneurial experimentation at the core of the new technical-economic paradigm. The positive externalities created by an environment in which information flows freely are a powerful, unintended consequence of the development of the new paradigm, which defines a new market structure.[41] All of these developments are fundamentally important to support a decentralized approach to energy supply.

SOLAR AND WIND: THE PUBLIC PRIVATE INNOVATION SYSTEM AT WORK

The development of the technologies that constitute the cornerstone of the emerging electricity system are prime examples of the intricate and intimate relationship between the state and the market. Simply put, "the solar industry owes its origin and existence to extensive government intervention."[42] The clarity of this conclusion flows from the obvious origins of the contemporary industry—the need for a source of electricity in space applications. That need was followed by a decision to continue to develop the technology,[43] first for other "off-grid" applications, but ultimately seeing far more growth in on-grid applications. The engine of development was the basic research that created the technological progress, in collaborative, jointly funded projects. A substantial percentage of the patents held by the leading solar companies (one-fifth to one-half for U.S. companies; one-fifth to one-third for non-U.S. companies) are tied back to the government-funded research. For well over a decade, government funds were the majority of the investment in the sector.

However, as Figure 4.3 shows, commercialization in on-grid applications were the future. Private sector investment swamped federal spending.

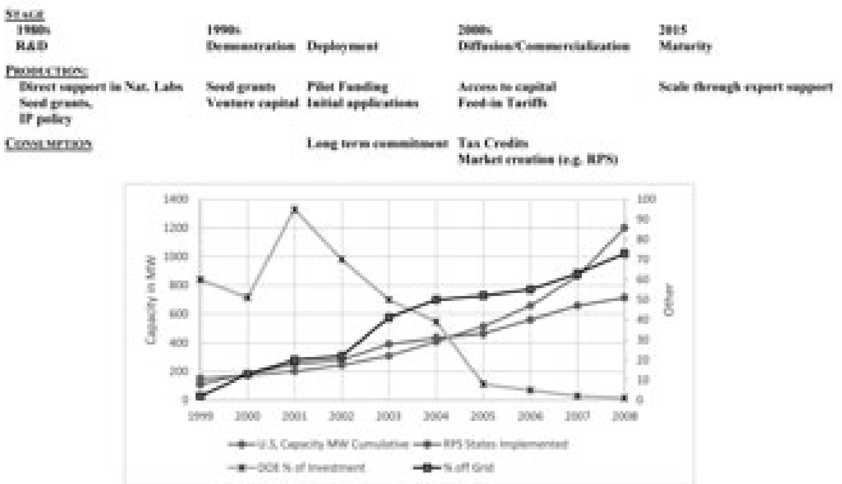


Figure 4.3 The Interconnection of Public and Private Activities in the Solar Technology Revolution

Sources: Roasalie Ruegg and Patrick Thomas, *Linkages from DOE's Wind Energy Program R&D to Commercial Renewable Power Generation* (Washington, DC: U.S. Department of Energy, 2009); Usha C. V. Haley and Douglas A. Shuler, "Government Policy and Firm Strategy in the Solar Photovoltaic Industry," *California Management Review* 54 (2011); R. Margolis, R. Mitchell, and K. Zweibel, "Lessons Learned from the Photovoltaic Manufacturing Technology/PV Manufacturing R&D and Thin-Film PV Partnership Projects" (Technical Report NREL/TP-520-39780, September, 2006); Gregory B. Upton, Jr. and Brian F. Snyder, "Renewable Energy Potential and Adoption of Renewable Portfolio Standards," *Utilities Policy* 36 (2015); Angely A. Carcamo Gallardo, "Adoption of Renewable Portfolio Standards in the United States: Which Factors Matter?" (Master's thesis, University of New Mexico, 2009).

At the key moment of transition, when private investment replaced public and on-grid replaced off-grid, the market was expanded with state programs to require renewable installations. The growth of the policy commitment, measured as the sum of the number of states that adopted a renewable portfolio standard and those that had implemented it (adoption being a measure of intent and implementation being a measure of execution), is an almost perfect predictor of the quantity supplied (measured as an exponent) through this transition period.

The upper part of Figure 4.3 also shows the evolution of key state activities across the lifecycle of the technology, using the 1980s as the period in which the effort to build a broad-based commercial sector was launched. The shift in policy focus has been studied in crossnational perspective, with the United States dominating the early production-focused stages, and others (e.g., Germany and China) becoming prominent in the later, consumption-focused stages. The federal commitment to directly promoting consumption has been inconsistent, with tax credits coming and going, but key states moved at this level. The movement at the state level should not be underestimated. By 2002, states with almost half the U.S. GDP had adopted an RPS. Taken together, these states today have a GDP that is twice the size of Germany and about three-quarters the size of China.

Table 4.3 provides a concrete example of the interplay between the private sector and the state, through policies that advance the technology and create the conditions for market success for the second-most important supply-side resource of the ongoing technological revolution: wind power. The table shows the discrete actions of the state and the private sector, as well as the rate of improvement in key aspects of the technology—improvements that add up to a technological revolution.

The process of supporting early development and sustaining support for deployment is a fundamental part of the pragmatic progressive capitalist model. It has played a crucial part in the deployment of every major technological infrastructure. As the economy becomes more advanced and networked, the role of the state in the early days seems to become even more important. This is because positive externalities, which are difficult for private actors to capture, play a larger part in dynamically interconnected networks. Here we see it for the two most important technologies that will define the 21st-century energy sector.

The same is true for the digital economy more broadly defined. Every one of the major technologies that provided the foundation for the digital revolution is grounded in the same process, in roughly the same period, for similar reasons—associated with space exploration, national defense, and a desire to support emerging sectors.

Table 4.3 The Interconnection of Public and Private Activities in the Wind Technology Revolution

	Precursors, context & table setting	**Time Period Early 1990s**				**Early 2000s**	
State Activities	Digital, computer, communications miniaturization technologies	DOE, ARPA-E National Laboratories Direct and Joint Projects University Support	Patent "giveaways" Tax Credits	Local Subsidies	State-based obligations & State Price policies	Broader stimulus	Mass Deployment
			Federal Procurement & Market Development				
Technology							
Public/Private Research	First wind rush	Turbines Aerodynamics Blades	Computer modelling Resource mapping				
Private Innovation Deployment			Lubricants	Lab testing Computerization of operations	Incremental innovation	Local maintenance	Load factor improvement
Finance							
Public		R&D, basic	Public/ private partnerships		Investment & tax credits Bankruptcy forgiveness		

(*Continued*)

Table 4.3 (Continued)

	Precursors, context & table setting	Time Period Early 1990s		Early 2000s	
Private		VC funding	Tax Levered capital	Stocks offering	Project finance
					Large mergers
<u>Average Annual Improvement</u>			1990s		2000s
Fixed to variable speed			4.7%		
Height					2.6
Sweep					9.8
Load factor					3.0
Output			8.5		
Overnight Cost			5.0		
O&M cost					−6.9
Cost/ kwh			−11.5		−2.2 (simple avg.)
					−4.0 (wtd. Avg.)

Source: Matt Hopkins, *The Making of a Champion or, Wind Innovation for Sale: The Wind Industry in the United States, 1980–2011*, AIR Working Paper #13-08/02 (Cambridge, MA: Academic-Industry Research Network, 2013); Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths* (New York: PublicAffairs, 2015), Chapter 7; Ryan Wiser and Mark Bolinger, *2014 Wind Technologies Market Report*, U.S. Department of Energy, August 2015.

Similar studies have been conducted on the third key resource we identify as a pillar of the 21st-century model: efficiency. These tend to be more varied, as the target energy-consuming durables are more diverse. Nevertheless, similar conclusions are reached, although a great deal more emphasis is placed on consumption policies later in the process (e.g., standards).[44]

Although state support throughout the lifecycle of core energy technologies has been a fundamental part of the process since at least the start of the technological revolution, in the heyday of market fundamentalism, these subsidies have become a constant target of attack. The response has been a systematic demonstration of the benefits of these efforts in terms of patents, declining costs, and very favorable cost-benefit ratios by both government agencies[45] and independent analysts.[46]

CONCLUSION

This new technical-economic paradigm dramatically improves economic performance because it facilitates economic activity at the micro level that had been hampered by traditional market barriers or imperfections (transaction costs, access to capital, market power, etc.). It has the effect of reducing a number of other market imperfections that previously hampered the macro-level performance of the system (provision of public goods, learning, spillovers, network effects, etc.).

As has always been the case, however, there is a struggle between the incumbent and new-entrant technologies over the speed and ultimate configuration of the new system, and which values will be expressed by that system. In short, the energy sector—particularly the electricity sector—is at the "turning point"[47] or "critical juncture"[48] of what we have termed the "quarter-life crisis of the digital political economy."[49] Political economy is about driving the economy in the right direction with policy. While the outcome is uncertain, the technological progress suggests that prospects are good for a successful deployment of the third Industrial Revolution in the electricity sector.

One of the great ironies of the ongoing struggle between central station resources (nuclear in particular) and the alternatives is the complaint that the alternatives are winning because they are favored with subsidies.[50] The argument is wrong on three counts. First, on a lifecycle basis, nuclear has received ten times the subsidies of wind and solar combined. Second, as discussed in the next chapter, onshore wind and utility solar are already the least-cost alternatives, having experienced a technological cost-reducing revolution. Third, the pay-off on investments in the renewable alternatives have only begun to be registered, a pay-off that nuclear never achieved.

PART III

THE COMPLEXITY OF RESOURCE SELECTION IN A LOW-CARBON ELECTRICITY SECTOR

5

THE COST OF ELECTRICITY IN A LOW-CARBON FUTURE

INTRODUCTION: APPROACH TO THE ECONOMIC ANALYSIS

The electricity sector is the heart of the long-term response to climate change and sustainable development, not only because the electricity sector is an important source of emissions, but also because decarbonization of the transportation and industrial sectors (which, when combined, are a larger source of emissions) requires a great deal of electrification of those end-uses. If electrification is central to decarbonization, the ability to deploy sufficient resources at affordable costs becomes the central challenge of delivering energy services in the 21st-century economy. Given the dramatic technological developments of the past quarter-century, the focal point of the challenge in the electricity sector is institutional—to deploy the physical and institutional infrastructure of a low-carbon sector.

In this analysis we take a long-term perspective, assuming that all costs are variable. This means that every generation asset online today must be replaced, so the analysis must focus on the cost of new "builds."[1] We extend the concept of "economic merit order"[2] to the long term. In the electricity system, "merit order" is usually applied to the decision about what resources to use in the short term based on their variable cost. Here, we compare the "economic merit order" of long-term resource acquisition based on total levelized cost to the "environmental merit order" of long-term, low-carbon resource acquisition based on total levelized cost within a constrained set of choices (low-carbon, low-pollution).[3]

The analysis focuses on the Jacobson et al. report because it provides the greatest detail across time, analyzes individual nations, and includes a comprehensive set of technologies from which to choose. Jacobson et al. impose two environmental constraints on resource acquisition—a carbon constraint and a constraint on other pollutants (e.g. particulates, gas emissions, waste, radiation, water pollution) and resource utilization (e.g. land and water). The authors add renewable resources to the generation portfolio for each nation based on the cost of those resources, which varies depending on the richness of the local resources.

Reflecting this structure, we ask how different the costs would be if the individual constraints were lifted. We assess the roadmaps in two steps. First we relax the pollution constraint; then we relax the carbon constraint.

This chapter, therefore, focuses on and "isolates" the direct economic cost of the technologies. Excluding the indirect costs and benefits of the carbon and other pollutant constraints is justified in part because the Paris Agreement is based on the decision to decarbonize the global economy. All of the deep decarbonization scenarios will reap the same carbon external benefits, but different mixes of decarbonizing technologies will have different costs and benefits in terms of economic resource costs and emissions of other pollutants.

This study concludes, however, that once the decision is made to decarbonize the economy, the impacts of other pollutants are of secondary importance for two reasons.

- First, the application of a rigorous least-cost approach to decarbonization accomplishes other pollution reduction goals as well. The lowest-cost, low-carbon resources are also the lowest in terms of the release of other pollutants, making the benefits of the reduction of these other pollutants "free."
- Second, even based on a standalone analysis, the set of alternatives that are least-cost with respect to other pollutants are also least-cost with respect to decarbonization.

The environmental merit order defined by each constraint is close to the economic merit order.

A CURRENT COST VIEW OF RESOURCE ACQUISITION

Current Costs

Figure 5.1 shows the mid-points for the levelized costs of various energy technologies as analyzed by Lazard in 2015. For the projected cost of natural gas with carbon capture and storage and battery storage, this review uses

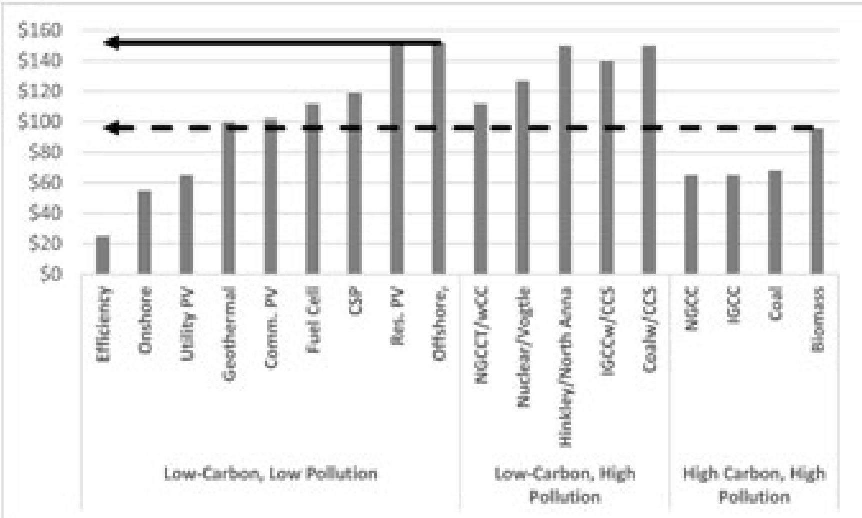


Figure 5.1 Lazard Levelized Cost of Energy Technologies, 2015

Sources: Lazard, *Lazard's Levelized Cost of Energy Analysis–Version 9.0,* November 2015. For Natural Gas Combined Cycle: Lazard, *Lazard's Levelized Cost of Energy Analysis–Version 7.0,* August 2013, average of high and low estimates except for point estimates for carbon capture (CC) technologies. For Hinkley reactor (UK): Mark Cooper, "Small Modular Reactors and the Future of Nuclear Power in the United States," *Energy Research & Social Science,* 3, 2014. For North Anna: Calculation based on "official" utility estimates (Sean Farrell and Terry Macalister, "Work to Begin on Hinkley Point Reactor Within Weeks after China Deal Signed," *The Guardian,* October 13, 2015; North Anna, Direct Testimony of Scott Norwood on Behalf of the Office of the Attorney General, Division of Consumer Counsel, Virginia Electric and Power Company, Integrated Resource Plan Filing Pursuant to Va. Code § 56-597 et. Seq., Case No. PUE-2015-00035, September 15, 2015, 5). Onshore = onshore wind; Utility PV = utility-scale PV; Geoth = geothermal; Comm. PV = commercial PV; CSP = concentrating solar power; Offshore = offshore wind; Res. PV = residential PV; GCCTw/CC = Natural Gas Combined Cycle with Carbon Capture; Vogtle = Vogtle nuclear reactor; Hinkley = Hinkley reactor (UK); IGCCw/CCS = Integrated Gasification Combined Cycle with Carbon Capture and Storage; North Anna = North Anna 3 reactor (US).

Lazard data from 2013 because these technologies were not included in the 2015 analysis.[4] Figure 5.1 includes the cost estimates for three new nuclear reactors: Vogtle, under construction in the United States; the proposed Hinkley reactor in the United Kingdom; and the proposed North Anna 3 reactor. We use Lazard's estimate for the cost of the Vogtle reactor.

The Vogtle construction schedule continues to slip, particularly compared to the builder's originally-advertised construction period, and the cost estimate continues to rise.[5] Therefore, we also show the cost estimate of the proposed Hinkley reactor in the UK, which is 20 percent higher than Lazard's Vogtle estimate.[6] Finally, we include a cost estimate for the proposed North Anna 3 reactor from a recent regulatory proceeding, which is about 33 percent higher than Lazard's Vogtle estimate,[7] but still 10 percent below a recent new reactor cost estimate from Australia.[8]

While these are current costs, and this analysis ultimately focuses on future costs, we use Lazard's estimates as an anchor point for two reasons. First, our previous analyses have generally relied on Lazard price projections more than others for a variety of reasons.[9]

- From the outset, Lazard's analysis included efficiency.
- Lazard's was among the first of the comprehensive analyses to note the strong downward trend in the cost of solar and to begin arguing that solar was cost-competitive for peak power in some major markets.
- The analysis always included estimates for coal with carbon capture and storage, and later added an estimate for the cost of natural gas with carbon capture and storage.
- The more recent analysis adds important storage technologies, utility-scale solar with storage, and utility-scale battery storage. It also presents a cost trend for storage that is similar to the trends from other renewable and distributed sources.
- The analysis always included natural gas peaking capacity costs and, in a recent analysis, added a cross-national comparison of peaking technologies that might displace gas as the peaker resource.

Second, because the electricity systems require the continuous management of resources, resource acquisition in the near-term is necessary. The compatibility/conflict between the economics of near-term and long-term resource acquisition is an important consideration. If there is a conflict, choosing resources becomes more difficult. In this instance, that is not the case.

Although Lazard estimates current or near-term costs, these data make an important point for the analysis of decarbonization. Three important resources—efficiency, wind, and utility-scale solar—are cost competitive now with the dominant central-station fossil fuels (natural gas and coal). These three resources account for over 60 percent of the need in the Jacobson et al. analysis. Under an assumption of more aggressive utilization of efficiency (that our review supports later in this analysis), these three resources reach almost three-quarters of the total need. They are also less than half the cost of new nuclear reactors or fossil fuels with carbon capture, and are widely available. Thus, based on current costs, the renewable resources that are the cornerstone of the 100 percent renewable scenarios should be the resources chosen today. There is no conflict between the assets that are preferable in the short-term and the long-term.

Figure 5.1 does not include the cost of peaking power for two reasons. First, they are off the charts, so high that they distort the overall picture. Second, peaking costs are one of the major economic costs that the 21st century approach reduces by matching supply and demand. The central station facilities "need" peakers that are very expensive and 21st century resources do not, although there are other costs that will be discussed below. Reducing peaks is a very valuable undertaking since peaking power is so costly and tends to be fossil fuel-fired. This is one of the reasons that storage, which had not been a focal point of investment and innovation, is now such a hotbed of activity.

"Merit Order" Analysis

Figure 5.1 organizes the Lazard costs according to the "environmental merit order" to frame the issues analyzed in this book. We divide the resources into three groups: resources that are low in carbon and other pollutants (low-carbon, low-polluting); those that are low-carbon, but high in other pollutants (low-carbon, high-polluting); and those that are high in carbon and high in other pollutants (high-carbon, high-polluting). The horizontal arrows show the resource that would complete the portfolio as constraints are lifted.

With the solid horizontal line in Figure 5.1, we can see that relaxing the pollution constraint, but keeping the carbon constraint, suggests that gas with carbon capture and storage could enter the portfolio depending on how much the lower-cost resources could expand. However, because the cost of gas with carbon capture is high, other renewable and distributed resources are cost competitive and also enter the portfolio. Therefore, other low-carbon resources would meet part of the need, pushing their share to about 85 percent, even without considering the expansion of the cost-effective resources beyond their original share. It also suggests that "forcing" Concentrating Solar Power (CSP) into the portfolio would have little impact on the total cost compared to natural gas with carbon capture and storage. At current costs, new nuclear does not enter the portfolio.

The dotted line in Figure 5.1 shows that relaxing both the pollution and carbon constraints allows unabated fossil fuels into the portfolio and squeezes the headroom for the expansion of efficiency, onshore wind, and utility-scale PV, even though they are competitive at current costs. However, this is at current prices. The future cost analysis later in this chapter paints a markedly different picture. Regardless of the constraints, efficiency, onshore wind, and utility scale PV are the dominant resources in all time frames.

The other clear conclusion from Figure 5.1 involves nuclear. It never enters the least-cost portfolio when economic cost is a criterion and costs are at the level of the U.S. Vogtle reactors. At the cost of the U.K. Hinkley reactor, nuclear barely competes with coal with carbon capture and storage. At the cost projected for the North Anna reactor and in the recent Australian analysis, nuclear is the most costly technology by far.

COST TRENDS AND THE FUTURE VIEW OF ECONOMIC MERIT ORDER

Cost Trends

Figure 2.1 above, shows that the capital costs of wind, solar, and nuclear have been headed in opposite directions since the negotiation of the United Nations Framework on Climate Change and are expected to continue to do so.[10] Overnight costs represent the economic cost of constructing these generation assets without financing costs taken into account.[11] Because fuel costs are relatively unimportant for these three resources, overnight costs are a good indicator of the relative levelized costs, with capital costs accounting for about 80 percent of wind and nuclear and 90 percent of solar levelized costs.[12]

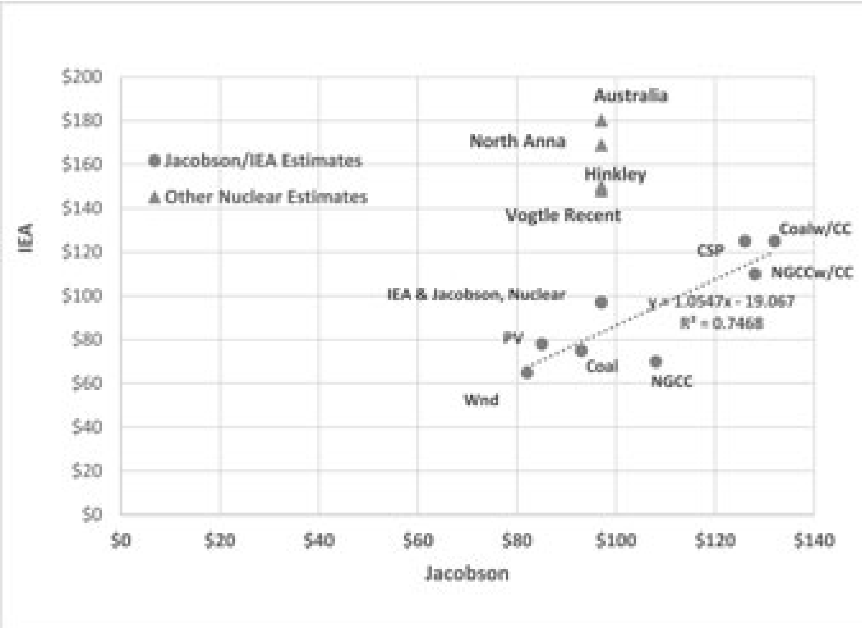
In the past decade, solar technology has experienced a dramatic cost decrease from a high level. Wind costs have been declining moderately from a relatively low level. Onshore wind costs are projected to be about half of offshore wind costs. Utility-scale PV costs have decreased from a moderate level to be competitive with wind. Nuclear costs have shown a continuous increase. By 2030, overnight costs of onshore wind and solar are projected to be less than one-fifth of nuclear. By 2030, offshore wind is projected to be somewhat below the current Hinkley and Vogtle cost estimates, and well below the North Anna and Australia estimates.

Another technology that has sharply declining costs, but does not play an important part in the Jacobson et al. analysis, is battery storage. The Australian study,[13] Navigant,[14] and Hoffman[15] project compound annual rates of declining battery costs in the range of 6 to 7.5 percent per year in the period from 2015 to 2030—the time period that is so crucial in the response to climate change. Lazard's projections of battery-cost declines in the short term is larger.[16] All analysts project rapid early cost reductions, then a flatting of the cost curve. In fact, some argue that when all of their potential values to the operation of the grid are taken into account, batteries are beneficial at today's costs and will be very attractive at future costs.[17] However, since careful planning of the acquisition of renewable resources (geographic deployment and technology selection) and active integration of supply and demand yield reliability that is equal to or exceeds the current reliability without batteries, the 100 percent renewable roadmaps do not rely much on storage, except in the case of CSP with thermal energy storage. Others who advocate for the transformation of the energy sector see storage playing a larger role.[18] In any case, storage represents a potential resource that could reduce the cost of the 100 percent renewable scenario and make it easier/less costly to ensure its viability.

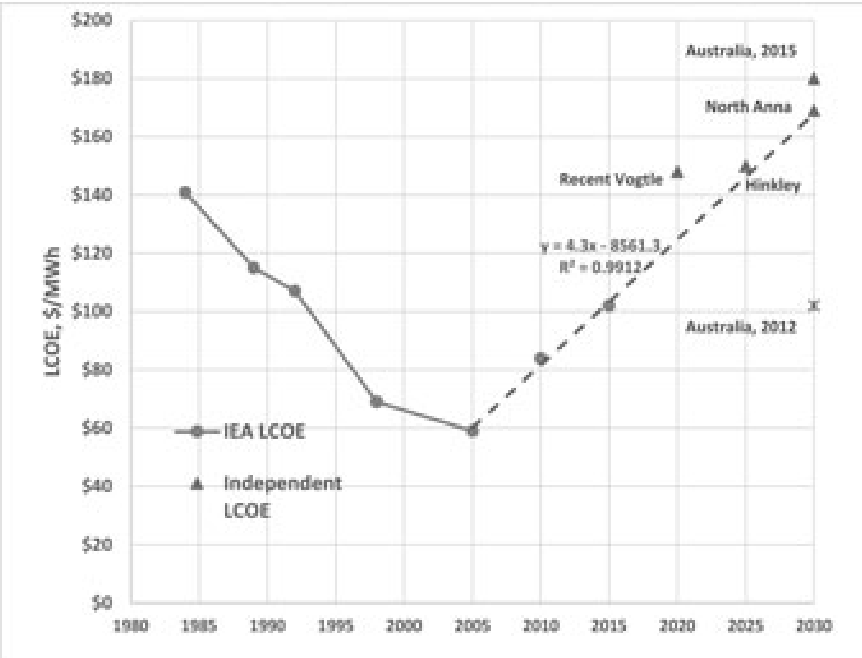
In contrast, there is a sharp divergence between some nuclear cost estimates and reality, as shown in the upper graph of Figure 5.2. Nuclear costs were severely underestimated about a decade ago amid the hype of a so-called "nuclear renaissance."[19] The problem is evident in the future projections as well, as shown in the middle and lower graphs of Figure 5.2. The International Energy Agency (IEA) cost projections, done in conjunction with the Nuclear Energy Agency, are quite low, as are the projections from the U.S. Energy Information Administration (EIA). Jacobson et al.'s cost projections are quite close to those of the IEA. The unfolding costs for Vogtle, Hinkley, and North Anna seem to be where costs are headed. Even the high cost estimate from Australia does not seem out of line. Figure 5.2 also shows the extremely low prior estimate of nuclear cost in the previous Australian study, which may have led the deep decarbonization pathway analysis (among others) astray.

In contrast to the nonhydro renewables, construction costs of commercial nuclear power in the United States over the course of 50 years have risen persistently without any indication of abatement. Small modular reactors (SMRs), which have been touted as the next big thing to save nuclear power, are likely to be much more costly than the renewables. Investment in SMRs has collapsed, with both Westinghouse and B&W—the two largest firms pursuing the technology in the United States—throttling investment.[20]

Although important local conditions can affect the cost estimates of power from alternatives (such as the richness of wind and solar resources), the broad technology cost trends tend to be global because technology is exportable. In fact, declining costs abroad have been greater than those in the United States despite the fact that the United States has richer resources. For example, solar costs declined almost twice as fast in Germany as in the United States after Germany made a strong commitment to increase reliance on renewables and decrease reliance on nuclear.[21] Cost trends for wind and solar in South Africa exhibit a similar pattern.[22]



Australia
North Anna
Hinkley
Vogtle Recent
Jacobson/IEA Estimates
Other Nuclear Estimates
CSP
Coalw/CC
NGCCw/CC
IEA & Jacobson, Nuclear
y = 1.0547x - 19.067
R² = 0.7468
PV
Coal
NGCC
Wnd
IEA
Jacobson
$0
$20
$40
$60
$80
$100
$120
$140
$160
$180
$200



Australia, 2015
North Anna
Recent Vogtle
Hinkley
y = 4.3x - 8561.3
R² = 0.9912
Australia, 2012
IEA LCOE
Independent LCOE
LCOE, $/MWh
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030

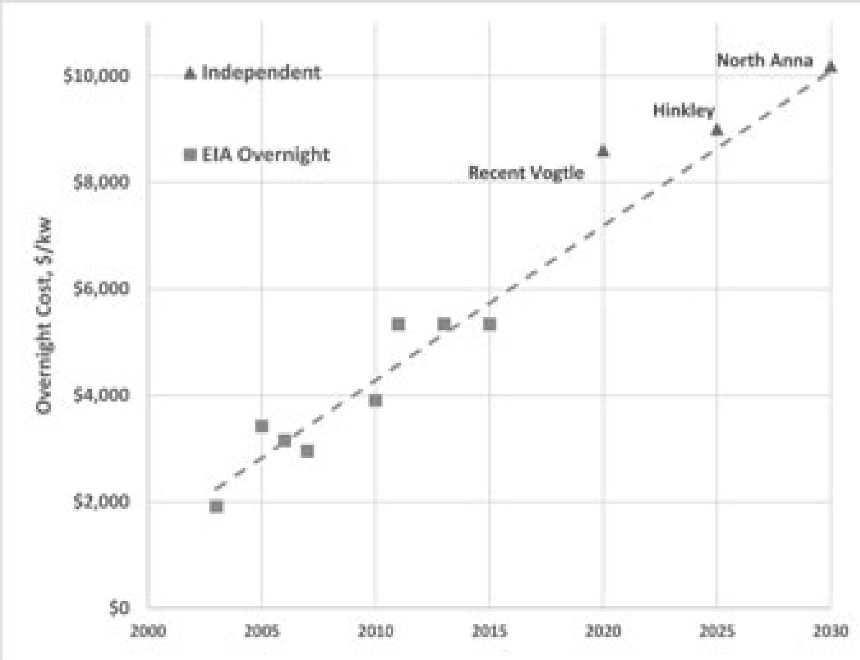


Figure 5.2 The Disagreement over Nuclear Cost

Sources: International Energy Agency (IEA) and Nuclear Energy Association (NEA), *Projected Costs of Generating Electricity: 2015 Edition*, September 2015; Energy Information Administration (EIA), *Updated Capital Costs for Electricity Generation Plants*, 2010 and 2013; Vogtle and Hinkley/North Anna, see Figure 2.1 and associated text; Electric Power Research Institute, *Australian Power Generation Technology Study* (Palo Alto, CA: EPRI, 2015); Bureau of Resources and Energy Economics, *Australian Energy Technology Assessment* (Australian Government, 2012).

> Renewables are cost competitive to even cheap against conventional generation. The clearing price for new wind and solar continues to fall with improvements in utilization and falling capital costs. For wind we are seeing utilization rates 15–20 percentage points higher than 2007 vintage turbines, regularly supporting PPA pricing at or below $30/MWH that effectively 'creates' long-term equivalent natural gas at <$3/MMBtu. Lower capital costs for solar have dropped PPA pricing to $65–80/MWH from well over $100/MWH, making solar competitive with new build gas peaking generation.[23]

EFFICIENCY AS A RESOURCE

In the above analysis of cost, efficiency is the least costly resource that anchors the supply-curve of low-carbon resources. Yet, as noted, most analyses of levelized cost of resources focus on generation alternatives and do not include efficiency. The cost of efficiency deserves much more attention. This section reviews the estimates of the cost of efficiency that underlie the efficiency gap. In the next section, the availability of efficiency as a resource to meet the need for electricity in a low-carbon environment is discussed.

To recognize efficiency as a low-carbon resource, Part IV examines the "energy paradox or energy efficiency gap."[24] For 30 years, economists, engineers, and policy analysts have authored engineering/economic analyses that showed technologies exist to potentially reduce the energy use of consumer durables (from lightbulbs to air conditioners, water heaters, furnaces, building shells, and automobiles) and producer goods (motors, HVAC, and heavy duty trucks). Because the reduction in operating costs more than offsets the initial cost of the technology, resulting in substantial potential net economic benefits, we confront the paradox: Why don't consumers purchase more economically efficient, durable goods that result in net economic savings?

The answer to that question is well-documented in hundreds (if not thousands) of empirical studies. Energy markets are imperfect and riddled with barriers and obstacles to efficiency, especially in the electricity sector. Market imperfections lead to underinvestment in energy-saving technologies. We will review that literature in Chapter 11.

The Cost of Saved Energy

The engineering economic analyses that provided the initial evidence for the efficiency gap showed that saving energy was significantly less costly than consuming it. *Ex ante* analyses indicated that there would be substantial net benefits from including technologies to reduce energy consumption in durable goods. As policies to spur investment in and deployment of energy-saving technologies were implemented, *ex post* analyses were conducted to ascertain whether the *ex ante* expectations were borne out. Those analyses strongly support the *ex ante* engineering analyses, as shown in Table 5.1.

Studies of actual costs—by Resources for the Future and the U.S. Department of Energy, for example—conclude that efficiency is well below the cost of energy. Forward-looking estimates from research institutions such as Lawrence Berkeley Labs and McKinsey & Company are similar. In fact, utilities and Wall Street analysts use similar estimates.

The most intense and detailed studies were conducted by utilities subject to regulation. Based on the results of utilities' analyses of the cost of efficiency in 16 states over various periods covering the last 20 years,

Table 5.1 The Cost of Saved Electricity (Cents per kWh)

Historical Analyses	
ACEEE	2.8[a]–3.5[b]
RFF Historical	6.0
LBNL	2.1[c]
Forward-Looking[d]	
RFF	3.0
LBNL	3.2
Lazard	2.5
PJM	3.0
McKinsey	2.8

Sources: a) Kenji Takahasi and David Nichols, *The Sustainability and Cost of Increasing Efficiency Impacts: Evidence from Experience to Date*, ACEEE Summer Study on Energy Efficiency in Buildings, 2008, 8–363; b) Maggie Molina, *The Best Value for America's Energy Dollar: A National Review of the Cost of Utility Energy Efficiency Programs*, Research Report U1402, American Council for an Energy Efficient Economy, 2014; c) Megan Billingsley et al., 2014, *The Program Administrator Cost of Saved Energy for Utility Customer-Funded Energy Efficiency Programs* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2014); d) The National Research Council relies on a study by Lawrence Berkeley Laboratory for its assessment: Richard Brown et al., *U.S. Building-Sector Energy Efficiency Potential* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2008; McKinsey & Company, "Unlocking Energy Efficiency in the U.S. Economy," *McKinsey.com*, 2009; National Research Council of the National Academies, *America's Energy Future: Technology and Transformation, Summary Edition* (Washington, D.C.: National Academies Press, 2009).

Takahashi and Nichols reach two findings that are important for the current analysis:

- The vast majority of costs fall in the range of $20/MWH to $50/MWH (i.e., 2 to 5 cents/kwh). The average is about $27/MWH, consistent with the estimate in Table 5.1.
- The higher the level of energy savings, the lower the level of costs. There is certainly no suggestion that costs will rise at high levels of efficiency.

The authors suggest that declining costs for higher levels of efficiency can be explained by economies of scale, learning, and synergies in technologies.[25] As utilities implement more of the cost-effective measures, costs decline. In addition, when technical potential is higher than achievable savings, then economies of scale, scope, and learning can pull more measures in without raising costs. This analysis supports the assumption that the cost of efficiency will not increase in the mid-term.

Consistent with these findings and observations, it is important to note briefly the analysis of minimum efficiency performance standards for consumer appliances and vehicles. There is a long (30+ year) and rich (20+ standards) history that affects billions of devices. This is precisely the type of broad and sustained impact that policies to promote and achieve the transformation to a carbon-free economy will have to have.

Table 5.2 shows the systematic overestimation by regulators of the cost of efficiency-improving regulations in consumer durables. The cost for household appliance regulations was overestimated by more than 100 percent and the cost for automobile regulations were overestimated by roughly 50 percent. The cost estimates from industry players were even further off the mark, running three times higher than actual costs for auto technologies.[26] Broader studies of the cost of environmental regulations find a similar phenomenon, with overestimates of cost outnumbering underestimates by almost five to one. Industry figures are considered a "serious overestimate."[27]

Table 5.2 The Projected Cost of Regulations: Percentage Overestimates of Costs

Appliances	Regulators
Room AC	
Small '82	70
Medium '82	130
Large '82	320
Small '90	520
Medium '90	60
Large '90	70
Central AC	160
Small '82	110
Large '82	130
Refrigerators	
1982	130
1995	1100
Washers	
1990	130

Vehicle	Regulators	Industry
Cafe 1975	150	50
California		
LEV I	140	740
I LEV	120	510
TLEVI	120	620
ULEV I	90	490
1996TI	170	360
Fuel Controls		
Phase 2 RVP	220	500
RFG-1	180	300
RFG-2	130	150
Diesel	100	150

Sources: Winston Harrington, Richard Morgenstern, and Peter Nelson, "On the Accuracy of Regulatory Cost Estimates," *Journal of Policy Analysis and Management* 19 (2000); *How Accurate Are Regulatory Costs Estimates?* (Washington, DC: Resources for the Future, 2010); Winston Harrington, *Grading Estimates of the Benefits and Costs of Federal Regulation: A Review of Reviews* (Washington, DC: Resources for the Future, 2006); Roland Hwang and Matt Peak, *Innovation and Regulation in the Automobile Sector: Lessons Learned and Implications for California's CO_2 Standards*, Working Paper, April, 2006; Larry Dale et al., "Retrospective Evaluation of Appliance Price Trends," *Energy Policy* 37 (2009).

Consistent with the empirical record, a simulation of the cost of the 2008 increase in fuel economy standards found that a technologically static response was three times more costly than a technologically astute response.[28] A recent analysis of major appliance standards adopted since 2000 shows a similar, even stronger pattern.[29] Estimated cost increases are far too high. There may be a number of factors that produce this result, beyond an upward bias in the original estimate and learning in the implementation, such as pricing and marketing strategies.[30] While the very high estimates of compliance costs offered by industry can be readily dismissed as self-interested political efforts to avoid regulation, they can also be seen as a worst-case scenario in which the manufacturers take the most irrational approach to compliance under an assumption that there is no possibility of technological progress or strategic response.

This explanation introduces an important area of analysis in the "energy gap" debate: learning curves. Policies to reduce the efficiency gap, such as performance standards, are intended to overcome market barriers and imperfections that have inhibited investment in efficiency. They have the effect of improving market performance. By overcoming barriers and imperfections, well-designed performance standards will stimulate investment and innovation in new energy-efficient technologies. A natural outcome of this process will be to lower the level of energy consumption as well as the cost of energy savings.

Out of an abundance of caution, in the long-term analysis we use the recent, higher ACEE estimate of the cost of efficiency, which is 40 percent higher than the midpoint of the Lazard range. This is cautious not only because current costs are lower, but also because some argue that costs will fall in the long term. While the historic data supports the hypothesis that there might be mild learning effects and economies of scale working, the transformation of the electricity sector may have a much larger effect on the cost of efficiency (see Table 5.3). Some have argued that changes in the relationship between the utility and the customer, as well as the broader range of approaches to efficiency made possible by the new ICT technology, could significantly lower costs. A reduction in transaction costs, improved targeting, and better monitoring of results can dramatically lower costs and improve the effectiveness of efficiency efforts. These effects are similar to the impact of the application of ICT technologies in other sectors.[31]

MERIT ORDER ANALYSIS BASED ON FUTURE COSTS

Figure 5.3 applies the "merit order" framework to the future costs utilized in Jacobson et al. As one would expect from the cost trends over time, the

Table 5.3 Potential Sources of Lower Cost/More Effective Efficiency in the 21st Century Electricity Sector

Traditional Approach	ICT-Driven Approach	Benefit
Narrowly targeted	Broad reach	Economies of scale
	Data-driven selection	Higher yield from better targeting
Time-intensive on-site assessment	Remote assessment	Lower cost
Capital intensive retrofits	Operational measures	Low cost, low-hanging fruit
"Measure by measure"	Holistic	Higher yield
Sporadic follow-up	Ongoing monitoring	More effective evaluation

Source: Dian Grueneich and David Joust, "Scale, Speed, and Persistence in an Analytics Age of Efficiency: How Deep Data Meets Big Savings to Deliver Comprehensive Efficiency," *The Electricity Journal* 27 (2014).

analysis using future costs shows that the economics of renewables improve in an absolute sense, and even more dramatically relative to the fossil alternatives. More renewable technologies are below the cost of low-carbon, high-polluting generation, and the headroom for additional renewables to be pulled into the portfolio is greater.

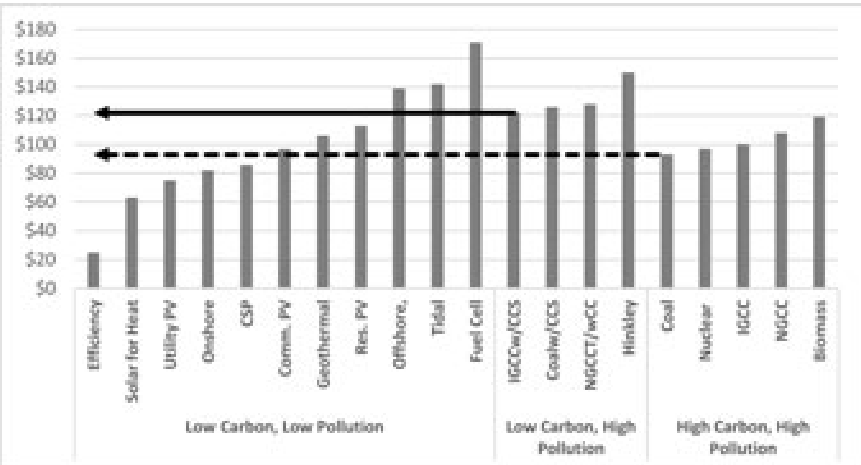


Figure 5.3 Environmental and Economic Merit Order, Jacobson et al. Future, $/MWh

Sources: Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries*, November 20, 2015.

Even when unabated fossil fuels are allowed to compete to enter the portfolio, efficiency, wind, and solar resources enter the portfolio first. Between 80 and 90 percent of the "environmental merit order" is the same as the "economic merit order," even in the unabated fossil case. Similarly, at the *Deep Decarbonization in Australia* costs, all of the major renewable resources enter under both the environmental and economic "merit orders." These findings are consistent with the strong consensus that has emerged in the financial and trade literatures, which is that the mid-term need for electricity will be met entirely without new coal or nuclear assets.[32] These analyses also see natural gas being backed out of the resource mix on economic terms.

REFINING THE ROUTE TO DEEP DECARBONIZATION

Minimal Cost Saving from Relaxing Environmental Constraints

In the above analysis, when we indicate that there could be competition at the margin for the final spots in the resource portfolio if either of the environmental constraints are relaxed, that does not mean that the "environmental merit order" would be more costly than a business-as-usual approach. Quite the opposite in fact, because the cost of the resources that make up the first three-quarters to nine-tenths of the "environmental merit order" are so much lower. In every case, building the resource portfolio with the renewable building blocks—efficiency, wind, solar (overwhelmingly utility scale PV)—would be less costly. The competition at the margin is only about how large the cost savings will be.

In the Jacobson et al. analysis for the United States with a carbon constraint only, the marginal resource needed would be nuclear, which would increase the cost savings by 10 percent because of the extremely low assumed cost of nuclear and the relatively large role of offshore wind. At Vogtle costs, the marginal resource would be coal with carbon capture, and the cost savings would be 5 percent. The result is similar with the higher costs of Hinkley or North Anna. If both the carbon and pollution constraints were relaxed, the marginal resource would be coal, and the marginal savings would be about 11 percent.

The outcome is uncertain because it depends on how much the low-cost resources could expand if one or both of the constraints are lifted. It can be argued that the environmental and economic "merit orders" are so close, leaving such a small amount of competition at the margin, that one or more of the lower-cost resources will expand to occupy the space left. Cost might go up, but not very much.

In the global analysis, the relaxation of the pollution constraint would lower costs about 5 percent (again, because of the unjustifiably low nuclear cost projected), while eliminating the carbon constraint would lower costs by 10 percent due to the smaller role of offshore wind. At the Vogtle cost of nuclear, the marginal resource is coal with carbon capture and storage, and the additional savings are even smaller. Thus, relaxing the constraint on other pollutants results in minimal cost savings. Therefore, the near-, mid- and long-term analyses identify essentially the same economic path to a low-carbon future.

Cost Savings from Increased Energy Efficiency

While we will not explore competition at the margin in detail, one area that is compelling and worthy of comment is the amount of energy efficiency that is assumed. Given the way efficiency is treated in the larger Jacobson et al. analysis, along with the fact that only modest gains in end-use efficiency are assumed, it seems reasonable to project a larger contribution from efficiency not only in the analysis of the lifting of constraints, but even in the base renewable case, as shown in Table 5.4.

Combining the business-as-usual and the transformation scenario, the total improvement in end-use efficiency is about 20 percent. The economic potential is larger than that today, and the technical potential is much larger. Moreover, the active management of demand in the transformation of the system has a dividend in reduced demand in the range of

Table 5.4 Impact of Merit Order Changes on Cost of Electricity, Jacobson et al. Average Levelized Costs (USD)[34]

Jacobson et al. Scenario	United States	Global
Current	108	103
BAU 2050	104	101
100% Renewable 2050	85	79
Allow Polluters	78	76
Allow Carbon Emitter	73	65
Jacobson et al. Scenario + 10% Efficiency		
Current	$108	$103
BAU 2050	104	101
100% Renewable 2050	72	68
Allow Polluters	77	65
Allow Carbon Emitter	72	64

Source: Based on Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries*, December 13, 2015. See text for a discussion of the data and methodologies. BAU = Business as Usual.

10 to 20 percent.[33] Therefore, it can be argued that higher end-use efficiency savings should be assumed and priced into the overall analysis. Although assuming an additional 10 percent of efficiency and pricing it into the analysis is conservative, as shown in Table 5.4, it has a large impact on the cost of the portfolio of assets.

Table 5.4 compares estimates for the impact of assuming a relatively modest 10 percent increase in efficiency from the base case. We find that efficiency more than offsets any cost increase associated with the environmental constraints, compared to savings that would result from lifting the constraint. Of course, one can argue that policy could achieve efficiency independently of the constraints so that the overall price would be even lower, but the difference is extremely small.

CONCLUSION

Thus, contrary to loud complaints that dealing with climate change will cause a disastrous increase in electricity costs, a rigorous, least-cost approach prevents such an outcome. It may even result in a reduction in the total cost of energy services, taking into account the cost of more efficient capital equipment powered by electricity and the very large potential for passive approaches to energy services.

We have shown that the "economic merit order" of resource acquisition is quite close to the "environmental merit order." Applying least-cost criteria in the context of a carbon constraint achieves the goal of pollution reduction.

- In the long term, the economic and environmental "merit orders" are almost identical. Because the cost of the low-carbon, low-pollution technologies has plummeted (and is expected to continue to decline), the shift away from baseload resources (fossil fuels and nuclear power) to reliance on flexible renewable resources—linked with active management of supply and demand—will lower the cost of electricity.
- Even in the mid-term, the "economic merit order" follows the "environmental merit order" to a large extent (75–90 percent, depending on costs used). Because the deviation of the "environmental merit order" is so small and the economic benefit of pursuing a 100 percent renewable electricity sector is so large, it does not seem worthwhile to relax the carbon/other pollutant constraints.
- In the short term, the main resources of the 100 percent renewable approach are currently less costly and widely available. Therefore, there is no reason to hesitate in pursuing the low-carbon, low-pollution path.

Given that this analysis assumes the massive electrification of the whole economy, the much smaller task of decarbonizing the electricity sector to meet the "traditional" need for electricity would be quite manageable. The technologies are in hand; we "merely" need to deploy them. The constraints are in the transportation and industrial sectors, where the necessary technologies are not as far along. The economic resource savings achieved by utilizing lower-cost, low-carbon, low-pollution resources largely "pays for" the transformation of the other sectors. The environmental and public health benefits of the transformation are surplus savings.

BEYOND COST: OTHER KEY FACTORS THAT INFLUENCE RESOURCE SELECTION

Having reached the conclusion that 100 percent renewable scenarios are attractive on the basis of the direct cost of the resources, we would be remiss in not dealing with other sets of factors that affect resource selection, as shown in Table 5.5. Indeed, while cost is always a focal point—if not the primary focal point—of resource selection, economic cost has never been the sole criteria by which electricity resources are selected. Other economic and noneconomic characteristics factor into which resource should be included in the portfolio of low-carbon resources.

The list of performance criteria by which the electricity system is evaluated varies from study to study, as Table 5.5 shows. However, it generally includes the following: economic costs (including financial, capital and operating cost), price volatility, reliability (including operational characteristics), variety, security (including availability and origin of fuel supply), flexibility (including operation and construction lead time), environmental impacts (including greenhouse gases, pollutants, waste, water, and land use), and social well-being (including health and consumption externalities).

This chapter considers two sets of factors beyond "simple" resource economics that frequently affect the acquisition of resources—investment risk and environmental impacts. We also address the critical questions of whether the resource base is adequate to meet the need, and whether the costs rise dramatically as the most attractive resources (defined by insolation, wind speed) are exploited.

TIME AND SIZE

Investment Risk

The factors that expose investors to risk are playing an increasingly important role in resource selection. The size of projects, time to market,

Table 5.5 Electricity System Performance, Characteristics, and Strategies

Multiple Performance Criteria →	Key System Characteristics →	Coping Strategies →	Strategy Effects
Stirling, 2010			
Financial	Technology	Risk Management	Portfolio Benefits
Operational	Combustion	Real Options	Hedging Ignorance
Supply security	Fossil v. Other	Portfolio	Mitigating Lock-in
Environmental	Non-combustion	Hedging	Fostering Innovation
Health	Geographic Scale	Diversity	Accommodating
Social Well-being	Local, Regional		Pluralism
	National, Global		Positive Synergies
	Resource		Portfolio Challenges
	Depleting, Non-		Negative Feedback
	depletable		Crowding Out
	Renewable		
Costello, 2005			
Economic	Technology	Hedge Against	
Operational	Type	Price	
Supply security	Lead Time	Supply	
Environmental	Intermittency	Reliability	
Social Well-being	Geographic	Regulatory Risk	
	Domestic	Fuel Diversity	
	Resource	Risk Management	
	Abundance	Portfolio Theory	
		Real Options	
		Theory	

Sources: Andrew Stirling, "Multicriteria Diversity Analysis: A Novel Heuristic Framework for Appraising Energy Portfolios," *Energy Policy* 38 (2010); Ken Costello, *Making the Most of Alternative Generation Technologies: A Perspective on Fuel Diversity*, NRRI, March 2005.

and sunk capital costs become an important consideration in an uncertain world with volatile prices. These concerns are reinforced by the urgency of dealing with the challenge of climate change.

In addition to the levelized cost of energy technologies discussed earlier in this chapter, we also provided estimates for key performance characteristics of these technologies. Small, nimble, quick-to-market assets are considered much more attractive investments. As shown in Table 5.6, there is a sharp distinction between central station resources and decentralized resources. Lazard uses a 69-month construction period, but the actual construction period for U.S. reactors is closer to ten years. Table 5.6 uses eight years as a cautious estimate.

Table 5.6 Cost, Capacity, and Construction Periods of Low-Carbon Resources

Resource	Size (MW)	Overnight Cost ($)	Construction (Months)	Sunk Cost (MW*$)	LCOE ($/MWh)
Renewable/ Distributed					
PV Rooftop Residential	.005	4,700	3	2,350	242
Microturbine	1	2,600	3	2,600	115
PV Rooftop Commercial	1	3,175	3	3,175	151.5
Solar PV-Community	1.5	2,400	6	3,600	107
Battery Storage	6	625	3	3,750	295
Fuel Cell	2.4	5,650	3	13,560	145.5
Solar PV-Utility	30	1,500	9	45,000	60
Biomass	35	3,500	9	122,500	102
Onshore Wind	100	1,475	36	147,500	59
Geothermal	30	5,450	36	163,500	100
Onshore Wind	100	4,300	12	430,000	55
Solar Thermal Electric	110	10,000	36	1,100,000	150
Offshore Wind	210	7,150	12	1,501,500	151
Central Station					
CC Gas w/CCS	550	6,500	42	3,575,000	127
Coal w/CCS	600	8,400	66	5,040,000	151
IGCC w/CCS	580	9,800	63	5,684,000	168
Nuclear	1,100	8,200	96	9,020,000	148

Source: Lazard, *Lazard's Levelized Cost of Energy Analysis 7.0*, August 2013; Lazard, *Lazard's Levelized Cost of Energy Analysis 9.0*, November 2015.

Central station, baseload facilities in general—and nuclear reactor construction in particular—are at a disadvantage compared to alternatives, which are more flexible and better able to meet small-load increases more quickly. As a result, the alternatives are easier to finance. The slowing of growth in demand, caused in the short term by the severe global recession and reinforced in the long term by improvements in energy efficiency, magnify the importance of small size and flexibility. The importance of climate change and niche applications are also magnified. In fact, small modular reactors (SMRs) are pitched as a response to these challenges, but the technology is still on the drawing board.[35] SMR deployment is a decade or more away, and numerous alternatives are already available that have more desirable characteristics. Thus, nuclear technology is, again, not competitive.

The investment characteristics discussed above—size, cost, and construction period—are presumed to expose the investor to several forms of risk, such as technology, marketplace, policy, and financial. Another form of risk that plays a particularly important role in the case of nuclear power is execution risk. Throughout its history, the construction of highly complex nuclear facilities has been plagued by construction delays and cost overruns, particularly in market economies. The current cohort of nuclear reactors under construction have experienced this problem.[36]

The Timing and the Task

While construction time plays a key role in driving the riskiness of investment, time plays a similar role from the environmental point of view. In a sense, the urgency expressed in the Paris Agreement suggests that time should be the first factor considered. All of the roadmaps require a significant change in the technologies used to produce and consume energy—essentially a transition to intelligent energy services. This includes active management and passive design to meet the much greater need for electricity required by the electrification of the industrial and transportation sectors. Given the current state of technological developments, some technologies can deliver much sooner than others in response to the urgency of the challenge.

Wind and solar, which will be the core technologies of the future global energy system, can deliver the needed power in large quantities more quickly. Over the course of the next 15 years, the load factors for wind and solar are likely to go up as the technologies improve and are combined with increasingly economic storage. Indeed, there are many deployments of these technologies that already exceed the load factor levels assumed above. This is all the more likely since, according to the economic "merit order" approach, much of the global deployment of renewable resources would be in virgin territories with rich resources.

In the analysis of Deep Decarbonization without the other pollutants, fossil fuels and nuclear end up claiming a significant portion of the portfolio. However, that contribution comes much later and results in electricity costs that are much higher. Through 2030, there is little contribution for new nuclear reactors and fossil fuels with carbon capture and storage. The Deep Decarbonization Pathways assume increasing contributions from nuclear and carbon capture in later years.

Both fossil fuel-based technologies and nuclear power, however, are much more costly. They would require long research, development, and deployment processes to get those costs down. Both would also have to solve significant environmental problems. The analysis of cost trends presented above suggests that an economic revolution in the traditional technologies is not likely in the near- or mid-term. The real-world experience of nuclear reactor construction does not support a claim that it can be brought online quickly. Construction periods in the United States increased throughout the history of the industry, averaging a decade. Current nuclear construction is well behind schedule throughout the world.

While nuclear construction periods in other countries are not quite as long as the United States, they are far longer than other technologies. Globally, nuclear construction periods are six times as long as renewable construction periods. The extreme urgency of climate change means that new nuclear will miss the critical period of the next decade, particularly if new nuclear technologies that are still on the drawing board are needed.

Time is of the essence. Jacobson has quantified the impact of the amount of carbon emissions associated with the "planning-to-operation" delays in deploying low carbon associated with large projects (as shown in Table 5.7). As the above analysis of construction period suggests, nuclear reactors suffer greatly in terms of carbon emissions. If the carbon opportunity cost of the "planning-to-operation" is taken into account, nuclear does not overlap with the main renewable/distributed resources even without taking research and development periods into account.

The data in Tables 5.6 and 5.7 challenge the claim that technologies based on fossil fuels with carbon capture or nuclear power are necessary to deal with climate change. The Greenpeace "revolution scenario" projects a level of low-carbon generation that equals the Deep Decarbonization Project projection with carbon capture, but without nuclear. Both the Greenpeace "advanced scenario" and Jacobson et al. project a level of

Table 5.7 Lifecycle Carbon Emissions with Lost Opportunity of Delay (Grams of CO_2/kwh)

	Life Cycle		Cost of Construction delay	
	Low	High	Low	High
Wind	4	7		
CSP	9	11		
Solar	19	59		
Geothermal	15	55	1	6
Hydro	17	22	31	49
Nuclear	9	70	59	106

Source: Mark Z. Jacobson, "Review of Solutions to Global Warming, Air Pollution, and Energy Security," *Energy and Environmental Science* 2 (2009): Table 3.

carbon reduction that exceeds the Deep Decarbonization Projection without either fossil fuels or nuclear.

Environmental and System Factors

There have been quantitative and qualitative efforts to assess and rank the resources in terms of their environmental impacts and sustainability. Jacobson et al. have quantified the large public health and environmental benefits of shifting to low-carbon, low-polluting resources. Table 5.8 combines qualitative and quantitative approaches to demonstrate the nature of these considerations. While the quantitative analyses frequently provide simple rankings, those simple measures do not do justice to the large differences between resources, as shown in Table 5.8.

Table 5.8 also shows the results of an older set of environmental evaluations conducted before climate change was a focal point of concern. Nuclear is seen as having a greater impact than gas, but a smaller impact than coal. The rank order of resources with respect to their noncarbon environmental impact is identical to that of the resource economics, which reinforces the earlier finding that efficiency, wind, solar, and natural gas are much more attractive resources. This table also supports the exclusion of hydro and biomass on the basis of their water use and emission of other pollutants.

The quantitative and qualitative ranks yield similar results that support a clear set of conclusions:

- The selection of resources on the basis of their environmental and sustainability characteristics would be almost identical to a selection based on their economic cost.
- Renewables have much smaller impacts, with the exception of land.
- The impacts of nuclear and natural gas are quite close to one another, especially when the delay in delivering nuclear reactors is taken into account.

Simply put, the environmental and economic "merit orders" fit hand-in-glove based on these considerations. In fact, the recent Australian cost study included a qualitative assessment of many of the factors considered by Jacobson et al. and reached similar conclusions.

One impact of the transition to a low-carbon economy that deserves special attention is the energy-water nexus. Water is an essential need for human life, a critical input to agriculture, and has been an important input for electricity generation. The central station-focused electricity sector is a huge consumer of water.[37] Electricity-generating technologies

Table 5.8 Evaluation of Externality Impacts of Resources

Resource	Water (m^3/MJ)	Carbon (g CO_2/kWh)	Land (m^2/GWh)	Pollutants (cents/kWh)	Avg. of Older Rankings
Renewable/Distributed					
Wave	0.001	68	202		
Tidal	0.001	68	202		
Geothermal	0.005	35	202	0.668	
Wind-BEV	0.01	13	2,404	0.29	0.533
Solar PV	0.042	58	1,232	0.69	0.553
Central Station					
Gas w/CCS	0.1	45	623	5.02	0.781
Coal w/CCS	0.31	90	325	14.87	1
CSP	0.41	10	510	0.69	0.553
Nuclear	0.59	40	78	8.63	0.798
Excluded Renewables					
Hydro	22	25	1,803	3.84	0.531
Biomass	40	59	18,116	5.2	0.994

Sources: Benjamin K. Sovacool and Michael H. Dworkin, *Global Energy Justice: Problems, Principles, and Practices* (Cambridge, U.K.: Cambridge University Press, 2014), Non-GHG: 149, GHG: 108; Benjamin K. Sovacool, "Exposing the Paradoxes of Climate and Energy Governance," *International Studies Review* 16 (2014); Mark Z. Jacobson, "Review of Solutions to Global Warming, Air Pollution, and Energy Security." *Energy and Environmental Science* 2 (2009): 165; Saeed Hadian and Kaveh Madani, "A System of Systems Approach to Energy Sustainability Assessment: Are All Renewables Really Green?" *Ecological Indicators* 52 (2015). Older Rankings are the average of Wilson B. Goddard, *A Comparative Study of the Total Environmental Costs Associated with Electrical Generation Systems*, G&GE Applied Research, 1997; U.S Congressional Office of Technology Assessment, *Studies of the Environmental Costs of Electricity* (Washington, DC: U.S. Government Printing Office: September 1994), evaluating Richard Ottinger et al., *Environmental Costs of Electricity* (New York: Oceana Publications, 1990); Paul Chernik and Emily Caverhill, "The Valuation of Externalities from Energy Production, Delivery and Use," a Report by PLC, Inc., to the Boston Gas Co., 1989; Olave Hohmeyer, *Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany* (Berlin, Heidelberg: Springer-Verlag, 1988); Michael Shuman and Ralph Cavanagh, *A Model of Conservation and Electric Power Plan for the Pacific Northwest: Appendix 2: Environmental Costs* (Seattle, WA: Northwest Conservation Act Coalition, 1982). BEV=battery electric vehicle; CCS = carbon capture and storage.

impact water from both the consumption and contamination points of view, both of which have been recognized in the broader environmental evaluations of resources.[38] Climate change and the response to it are also likely to magnify the importance of the energy-water nexus.[39] The examination of water reinforces the earlier conclusions. Central station facilities consume and pollute more water. The renewables excluded by Jacobson use more water and have higher pollutants than the other renewables.

There is a great debate among central station advocates about the relative impact of rare but catastrophic nuclear accidents that severely disrupt large regions compared to much more frequent, but much smaller, accidents associated with fossil fuels that affect much smaller areas. The data plotted in Table 5.9 indicate that, regardless of the outcome of the debate between nuclear and coal, the renewable and decentralized resources fare better on the accident dimension, again reinforcing the conclusions of each of the earlier analyses.

The environmental impact assessment of resources tends to focus on generation options and does not include efficiency. It is important to explicitly recognize efficiency because it certainly has the smallest impact. It highlights the complete array of positive and negative impacts of energy choice that is becoming widely recognized and consistently modeled. The fullest expression of externalities can be recognized in the decision not to consume.[40]

A list of nonenergy impacts of energy efficiency can be found Table 5.10, including all of the impacts of energy consumption and avoided production. An evaluation of the nonenergy benefits of whole-house retrofits produces a similar, long list of benefits.[41] The magnitude of these potential

Table 5.9 Accident Related Fatalities (Ranked with PV = 1)

Resource	Mean	Standard Deviation
PV	1.00	1.00
Geo Binary	1.62	4.73
Geo Flash	1.69	0.29
CSP	3.08	2.12
Offshore Wind	3.55	3.72
Onshore Wind	4.00	1.41
Biopower	4.18	1.31
CSP – MB	5.23	2.84
Nuclear	7.08	3.66
Coal	9.66	1.36
Hydro	12.13	8.83
Gas CC	19.66	6.20

Source: Sharon J. Klein and Stephanie Whalley, "Comparing the Sustainability of U.S. Electricity Options through Multi-Criteria Decision Analysis," *Energy Policy* 79 (2015).

Table 5.10 Two Views of Benefits of Efficiency as Externalities

	REGULATORY ANALYSIS PROJECT		
	Utility System	Participant	Societal Nonenergy
OECD/IEA			
Economic			
Provider Benefit & Infrastructure	Generation, Transmission, Distribution, Line Loss, Reserves Credit & Collections		Reduced Terminations Reduced Uncollectibles
Energy Prices	Demand Response Price Effect		
Public Budgets			
Energy Security	Reduced Risk	Societal Risk & Security	
Macroeconomic		Employment, Development Productivity, Other Economic	
Social			
Health		Health, Comfort, Bill Savings	
Affordability		O&M, Other Resource Savings	
Access		Low-Income Consumer Needs	
Development	Development		
Job Creation		Employment	
Asset Values		Property Values	
Disposable Income			
Productivity		Productivity	
Environment			
GHG Emissions	Avoided Regulatory Obligations & Costs		Avoided Regulatory Obligations & Costs
Resource Mgmt.			Electricity/ Water Nexus
Air/Water Pollutants			Air Quality Water Quantity & Quality Coal Ash & Residuals

Sources: James Lazar and Ken Colburn, *Recognizing the Full Value of Energy Efficiency: What's Under the Feel-Good Frosting of the World's Most Valuable Layer Cake of Benefits* (Montpelier, VT: Regulatory Assistance Project, 2013), p. 6; Lisa Ryan and Nina Campbell, *Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements* (Paris, France: International Energy Agency, 2012), 25.

gains is difficult to estimate, but likely to be substantial. The noneconomic benefits of energy efficiency are estimated to be 50–300 percent of the underlying energy bill savings.[42] The broad benefits of efficiency reinforce its role as the cornerstone of the low-carbon resource portfolio. We also note that this comprehensive view of the benefits of efficiency includes many of the key system operation issues that will be discussed in the next chapter (e.g., demand response, reduced investment in all types of facilities, more efficient generation).

THE EMERGENCE OF SUSTAINABILITY ANALYSIS

The current view of externalities has extended to the broader issue of sustainability of generation resources,[43] and it has also begun to look at important interactions between climate change and noncarbon externalities like heat waves and water use.[44] A concept of sustainability is being used more frequently to describe the nonenergy impacts of different technologies and resources.[45]

Once we move into the broader realm of the electricity system's noneconomic goals, nuclear power fares very poorly. Nuclear power has significant disadvantages in terms of security[46] and proliferation risks,[47] and continues to suffer from unique environmental problems.[48] As a result, in multiattribute rankings and evaluations, the main renewables (wind, solar, hydro) and efficiency are much more highly-rated[49] and have consistently been so for decades.[50]

In these sustainability studies, each technology is evaluated based on the application of four primary criteria:

- Financial: financial value of the technology and return on investment.
- Technical: characteristics of the technology as a power source and its production capabilities.
- Environmental: impact of power plant on local and regional environment, as well as human health.
- Social/Economic/Political: impact on local economy and communities, as well as congruence with overall national policies.[51]

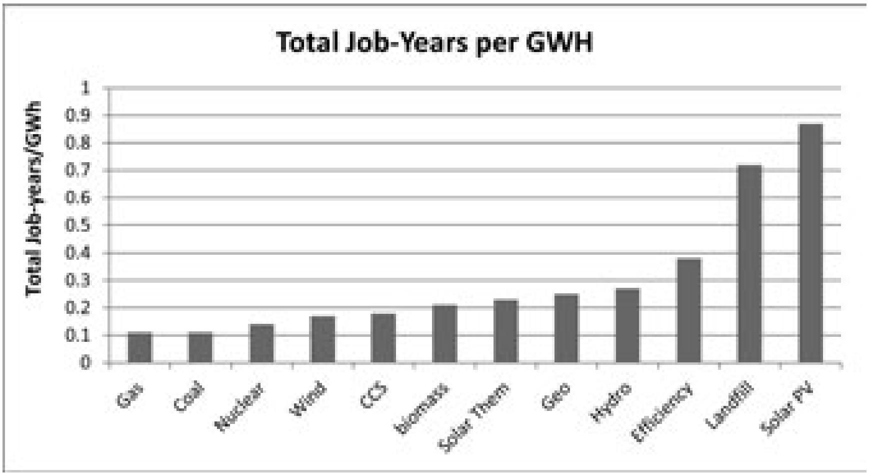
> The results indicate that wind, solar, hydropower and geothermal provide significantly more overall benefits than the rest even when the weights of the primary criteria clusters are adjusted during sensitivity analysis. The only nonrenewable sources that appear in three of the 20 top rank positions are gas and oil, while the rest are populated with renewable energy technologies. These results have

> implications for policy development and for decision makers in the public and private sectors. One conclusion is that financial incentives for solar, wind, hydropower and geothermal are sound and should be expanded. Conversely, subsidies for nonrenewable sources could be diminished.[52]

No discussion of other factors involved in the resource selection process would be complete without mention of macro-economic impacts of the transformation of the electricity system. While this is a hot political issue in the wake of the lingering effects of the great recession, one that has significant short-term distributional impacts, from a long-term perspective, it is less dramatic. Given that over the course of several decades almost all productive assets will have to be replaced, differences between systems will be more distributional—capital versus labor, geographic distribution, rents and profits earned by various owners of resources, and so on.

Using an econometric model, Jacobson et al. concludes that the 100 percent renewable scenario will add about 1 percent to global employment, counting construction and operation jobs. Studies of the direct impact of resources on jobs indicate that the alternatives create more employment per dollar of output, as shown in the upper graph of Figure 5.4, and a general proposition, spending on energy produces fewer jobs than nonenergy spending. Because the renewable/distributed/demand-based approach is projected to lower costs and produce much larger public health benefits, the indirect macroeconomic stimulus from the transformation is likely to be positive and significant.

The emerging 21st-century technoeconomic paradigm for the electricity sector is superior to the 20th-century central station-approach on every criteria. Economically, it is now lower in cost with strong trends increasing its advantage, quicker to market with smaller scale assets that lower risk and provide a larger macroeconomic benefit. Environmentally, it is cleaner with respect to carbon and other pollutants and its speed to market makes it a much better candidate to address climate change, and it has much smaller impacts with respect to water use and accidents. The one area where it might be at a disadvantage is land use, where the impact can be mitigated to a considerable extent by careful site election and use.



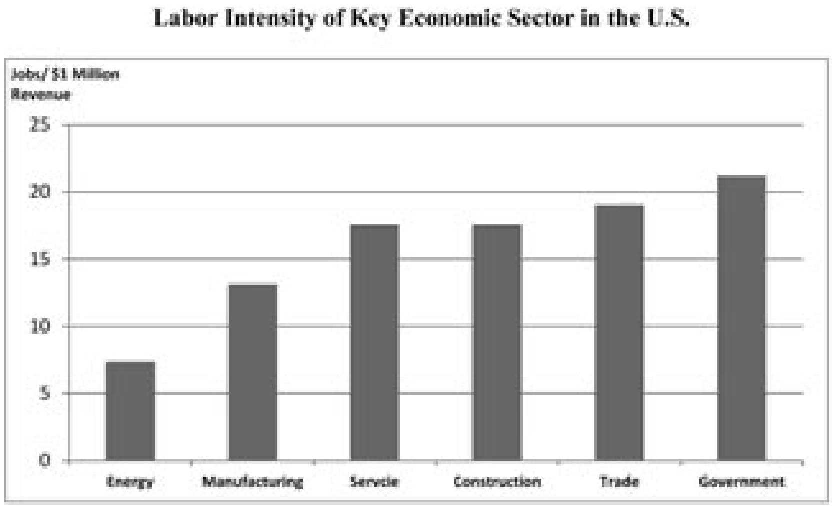


Figure 5.4 Job Creation by Alternative Approaches to Meeting Electricity Needs

Sources: Upper graph–Max Wei, Shana Patadia, and Daniel Kammen, "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?" Energy Policy, 38 (2000). Lower graph–Rachel Gold, et al., "Appliance and Equipment Efficiency Standards: A Money Maker and Job Creator," *American Council for an Energy Efficient Economy,* January 2011, p. 9, based on the IMPLAN Model, 2009.

6

ENERGY POTENTIAL AND INSTITUTIONAL RESOURCE NEEDS

ENERGY RESOURCE POTENTIAL

Assuming the urgent need for decarbonization, the previous two chapters have demonstrated that central station resources (nuclear power and fossil fuel generation) are at a severe economic disadvantage as renewable/distributed/efficiency technologies continue to develop and deploy. A resource is not a system, however, and resource costs are not the only factor that must be considered.

First and foremost, the resource base must be sufficient to meet the needs for electricity over the long term, but the size of the resource base is a function of the technologies available to exploit it. Second, the resources must be combined and operated to yield a stable, reliable system of supply. This chapter examines the resource potential. The next chapter examines the institutional infrastructure needed to create the system.

THE IMMENSE RESOURCE BASE FOR A 21ST-CENTURY ELECTRICITY SYSTEM

Global Potential

The possibility that renewables could become the primary source of energy in the decarbonized electricity sector has been recognized by major research institutions. As the MIT study on *The Future of Solar* puts it,

> Massive expansion of solar generation worldwide by mid-century is likely a necessary component of any serious strategy to mitigate climate change. Fortunately, the solar resource dwarfs current and projected future electricity demand. . . .

> Solar electricity generation is one of very few low-carbon energy technologies with the potential to grow to very large scale. As a consequence, massive expansion of global solar-generating capacity to multiterawatt scale is very likely an essential component of a workable strategy to mitigate climate change risk.[1]

The Department of Energy said much the same about the potential for wind in its *Wind Vision Report*:

> Interest in wind power is stimulated by its abundant resource potential (more than 10 times current electricity demand); competitive, long-term stable pricing; economic development potential; and environmental attributes, including its ability to support reduced carbon emissions, improved air quality, and reduced water use.[2]

Both of these analyses recognize key challenges that must be overcome to achieve high levels of reliance on renewables. However, both of the analyses are optimistic about the ability to do so.

MIT identified three key challenges—

> We focus in particular on three preeminent challenges for solar generation: reducing the cost of installed solar capacity, ensuring the availability of technologies that can support expansion to very large scale at low cost, and easing the integration of solar generation into existing electric systems. Progress on these fronts will contribute to greenhouse-gas reduction efforts, not only in the United States but also in other nations with developed electric systems. It will also help bring light and power to the more than one billion people worldwide who now live without access to electricity.[3]

At the same time, the MIT study points to real world experience that suggests the path to overcoming these challenges is clear, adding recommendations for public policy to support that effort.

> A number of emerging thin-film technologies that are in the research stage today use novel material systems and device structures and have the potential to provide superior performance with lower manufacturing complexity and module cost. Several of these technologies use Earth-abundant materials (even silicon in some cases). . . .
>
> Experience in Germany suggests that several components of BOS [Balance of System cost, other than solar panels], such as the cost of

> customer acquisition and installation labor, should come down as the market matures . . . net load peaks can be reduced—and corresponding cycling requirements on thermal generators can be limited—by coordinating solar generation with hydroelectric output, pumped storage, other available forms of energy storage, and techniques of demand management. Because of the potential importance of energy storage in facilitating high levels of solar penetration, large-scale storage technologies are an attractive focus for federal R&D spending.[4]

Geographic Distribution

As noted above, the technical potential of each of the renewable resources is huge compared to the current and projected need for electricity. While the geographic distribution of each renewable resource is not uniform, there is ample availability of resources when the two major renewable resources (solar and wind) are combined. A 2012 study by the National Renewable Energy Laboratory (NREL) looked at the ratio of potential resources compared to electricity sales in 2010. The calculation of the potential was based purely on technical considerations,[5] using load factors of about 20 percent for solar and 30–40 percent for wind, which are consistent with real world experience and likely to improve over time. For half the states, the renewable resources are more than 50 times consumption. For two-thirds of the states, the renewable resources are more than 25 times the level of consumption.

Only four states had a ratio less than ten. The states on the lower end of the range, however, lie in regions/are part of regional service areas (regional transmission organizations or reliability areas) with states that have much higher levels of potential renewable resources. As discussed below, expanding the geographic footprint of the system and integrating different technologies greatly improves the ability of the system to meet needs with renewable/distributed/efficiency-based approaches. These findings are consistent with the observations of the Department of Energy and the academic literature. The projected level of wind and solar in 2030 is just under 40 percent, which is in the range that NREL analysis finds easily attainable.[6] The projected level in 2050 is just under 80 percent, which requires a significant degree of transformation of the system, but is deemed achievable.

There is no doubt that the technical potential vastly exceeds the long-term need, and the economic potential is adequate to meet the mid-term need. The uncertainty comes in the continued development and declining cost of renewable technologies and the implementation of policies to integrate the renewables into a stable, reliable electricity system. These observations support the conclusion that the electricity sector is on the cusp of a major transformation. As discussed below, independent financial analysts are also signaling the dramatic impact that the emergence of the 21st-century electricity market could have on the 20th-century utility business model.

Global resource maps show that solar should play a leading role, but wind is also a plentiful resource in specific areas. This is consistent with the projections above in Table 2.2, showing solar and wind as the two primary resources.

In the United States, areas that lack solar resources have wind resources. The Southeastern United States is a region where the renewable resources base was somewhat restricted, but it still has 10 times demand. Northern Europe, which has limited solar resources, has abundant wind resources. In many of the areas of the world where the wind resource is in short supply, hydro is quite plentiful.

The palate of potential renewable resources is rich. The regions of the world where the overwhelming majority of people reside generally have at least one of the major nonhydro renewables in abundance. Because the resources are widely distributed, they can strengthen local economies and contribute to local energy security, which was a stated goal of the Paris Agreement, as noted in Chapter 2. The optimum portfolio will vary according to which resource is richest in a given area, but geographic, technological, and resource diversity are extremely valuable, making broad transmission areas crucial.

The commanding position of efficiency and renewables (in terms of the resource economics and other factors) is one of the major forces driving change in the electricity sector, but it is not the only force. Table 6.1 lists additional factors that have been driving change and increase the likelihood that an alternative system can be constructed to meet the need for electricity.

Mid-Term Potential

While academics and government agencies have been looking at the long-term resource potential for quite some time, the new voices in the conversation are the financial analysts who focus on the near- and mid-terms, since that is the time frame in which the advice to investors is most relevant. In this book and in earlier analyses, we have shown that these financial analysts have been at the forefront of raising important issues when it comes to nuclear power including

- questioning the unrealistically optimistic cost projections offered by advocates in the early days of the "nuclear renaissance," and warning that new reactor construction would place severe burdens on utility finance;[7]

Table 6.1 Trends and State of Play in the System Transformation

	Resources Potential	Systemic Operation
Trends:	Renewable cost reduction Rising cost of conventional Slow demand growth Self-supply	Growth of decentralized supply Diverse participation in markets Customer engagement Interaction with other sectors and power suppliers Growth of ICT in grid operation
State of Play:		
Near/mid-term	Cost competitive	Costs and benefits under intense analysis
	Adequate for steady path to long-term goal	Demonstrated to moderate levels (30–40%)
Long-term	Solar: Resource dwarfs need Wind: Resource exceeds need	Tools for high levels (65%+) identified
Challenges:	Incumbent resistance to change New business models needed Regulatory inertia Rate structure Investment incentives Wind: Offshore cost Solar: storage, balance of system costs, common element resource base Beyond resource economics: security, reliability, resilience, environment	Entrant resistance to oversight Deployment of intelligent infrastructure Physical Institutional

Source: Author.

- identifying the implications of the dramatically declining cost of alternatives—wind, solar, and storage;[8] and
- recognizing the economic problems of aging reactors in wholesale markets where renewables and efficiency are putting downward pressure on prices.[9]

Therefore, we should not be surprised to find many of these analysts signaling the potential for dramatic change in the structure of the utility industry. That analysis begins with the economic building blocks for a transformation of the electricity sector, centered on renewables, distributed resources, and efficiency. Half a decade ago, these analysts had concluded that transformation of the electricity system was under way, driven by the economics of renewable/distributed/demand-based resources.

A late 2012 analysis from Citi Research concluded that "residential-scale solar is already competitive with electricity off the grid. . . . Utility-scale solar will be competitive with gas-fired power in the medium term. . . . Utility-scale wind is already competitive with gas-fired power."[10]

Credit Suisse took an even more aggressive view of the development of renewables. They argue that over the next decade, renewable deployment will be so substantial it will meet five-sixths of the need for generation, resulting in reduced pressure on gas supply. While Credit Suisse cites policies that are promoting renewables as the context for its transformational impact on supply, it also argues that renewables have become cost-competitive with conventional baseload generation.[11]

> We see an opportunity for renewable energy to take an increasing share of total US power generation, coming in response to state Renewable Portfolio Standards (RPS) and propelled by more competitive costs against conventional generation. We can see the growth in renewables being transformative against conventional expectations with renewables meeting the vast majority of future power demand growth, weighing on market clearing power prices in competitive power markets, appreciably slowing the rate of demand growth for natural gas.[12]

McKinsey & Company reached the same conclusion as Citi and Credit Suisse in projecting cost parity for solar and conventional generation within the next decade. Lazard argues we are already there in many markets,[13] and RMI projects widespread grid parity within a decade.[14] They argue that the growth of solar could have an "outsize" effect by reducing the demand for baseload generation, and could "seriously threaten" utilities "because its growth undermines the utilities' ability to count on capturing all new demand, which historically has fueled a large share of annual revenue growth. (Price increases have accounted for the rest.)"[15] Even though the market share of renewable is relatively small in the near term, the net effect is to shift the demand for resources and undermine the ability to raise capital for baseload generation.

> By altering the demand side of the equation, solar directly affects the amount of new capital that utilities can deploy at their predetermined return on equity. In effect, though solar will continue to generate a small share of the overall U.S. energy supply, it could well

> have an outsize effect on the economics of utilities—and therefore on the industry's structure and future.[16]

The importance of the impact of renewables at the margin was also emphasized by analysts at Sanford Bernstein. Reflecting on a debate in California, they note that the effect at the margin is much larger than one might think given relatively small market share: "Two things stand out. First, this is a live issue in one of the largest power markets in the world, with solar at .17 percent of global demand. Second, trends that start in California tend to travel well."[17]

> We think it is realistic to expect at least 30–40 percent reduction in cost per watt in key solar markets, while the greatest cost reductions are likely to come from the residential segments as scale and operating efficiencies improve. There is historical precedent for this in the oldest major solar market in the world—Germany. . . .
>
> Lastly, the power of all-in cost should not be underestimated. A typical residential US-based system costs around ~$25–35K today, but we believe that comparable residential systems could easily dip into the $10–15K range over the next 5 years if market forces driving cost reduction are allowed to progress without substantial policy/exogenous shocks. If interest rates are reasonable and a homeowner takes out a loan, upfront capital investment would be as little as a few thousand dollars.[18]

Energy Savings

Many financial analysts who project the important role that renewables can play in meeting the need for electricity in the mid-term also note a similar role for efficiency. Credit Suisse suggests that declining demand growth helps to drive the transition of the electricity sector.

> The impact of energy efficiency has become more of a focal point after another year of lackluster power demand growth in 2013 and disappointing usage trends across customer classes.[19]
>
> Our take: Energy efficiency remains an under-appreciated but very important trend in power markets that will lead to structural drags on power demand growth impacting the outlook for competitive power market recovery and where utility capex will need to be allocated. We model efficiency-lowering annual demand growth by ~70 bp (.7%) a year from a 'normal' baseline, putting core growth at +0.5.1.0% with downside risk barring better economic recovery. . . .

> Our outlook for slower demand growth relative to a 'normal' +1.5% pushes out reserve margin equilibrium by 1–3 years, creating another unwanted headwind for competitive power.[20]

Credit Suisse explains that the slowing of demand growth places a great deal of pressure on the economics of utilities, not only where it adds to the downward pressure on prices set in markets, but also in regulated states where rate structures have relied on growing demand to ensure recovery of fixed costs.[21]

McKinsey & Company were among the first to propose the important role of efficiency.[22] However, beyond the fact that efficiency lowers the cost of carbon reduction, efficiency has two impacts on the economics of resource acquisition. First, as demand growth slows, the addition of large, central station facilities adds very large increments of supply that may result in excess capacity. Second, in the near term, efficiency is a response that buys time for alternative technologies to develop. Given cost trends, this improves the prospects for renewables, whose costs have been falling.

The potential for energy savings is substantial, as shown in Table 6.2. Several major research institutions estimate that there is great potential to reduce the consumption of each of the forms of energy (electricity, natural gas, gasoline, and diesel), all of which are substantial emitters of carbon.[23] Table 6.2 shows that a 20–30 percent reduction in consumption of energy sources consumed directly by households is technically feasible and economically beneficial. Much larger gains are technically feasible, but were not economically beneficial at the time of the analysis. As energy prices rise and innovation lowers costs, the technical potential becomes economically beneficial.

Table 6.2 also shows large economically beneficial and technically feasible potential efficiency improvements in transportation fuel consumption. Although a significant part of these potential savings are in improvement in liquid-fuel engines, a part of it also comes from improved vehicle design, drive train engineering, and rolling resistance. As fossil fuels are replaced by electric vehicles, improvements in liquid-fuel engines will not reduce the future need for electricity (as new electric power systems are required), but the other efficiency gains will.

"NEW" RESOURCES: DEMAND RESPONSE, STORAGE, AND INTELLIGENT INTEGRATION

We placed quotation marks around "new" in the title of this section to underscore the fact that, while demand response and storage have been

Table 6.2 Economic Potential Efficiency Gains

	% Reduction in Consumption
Economic Potential	
Electricity	
NRC 2030[a]	32
McKinsey 2020[b]	28.4
ACEEE 2030[c]	27.3
Gasoline/Diesel	
NRC 2030	~40
NHTSA-EPA[d]	~50

Source: a) The National Research Council of the National Academies, *America's Energy Future: Technology and Transformation, Summary Edition* (Washington, D.C., 2009) relies on a study by Lawrence Berkeley Laboratory for its assessment (Richard Brown, Sam Borgeson, Jon Koomey, and Peter Biermayer, *U.S. Building-Sector Energy Efficiency Potential* (Lawrence Berkeley National Laboratory, September 2008); b) McKinsey Global Energy and Material, *Unlocking Energy Efficiency in the U.S. Economy* (McKinsey & Company, 2009); c) Kenji Takahasi and David Nichols, "Sustainability and Costs of Increasing Efficiency Impact: Evidence from Experience to Date," *ACEEE Summer Study on Energy Efficient Buildings* (Washington, D.C., 2008), pp. 8–363; Molina, Maggie, 2014, *The Best Value for America's Energy Dollar: A National Review of the Cost of Utility Energy Efficiency Programs*, American *Council for an Energy Efficient Economy;* d) U.S. Environmental Protection Agency and Department of Transportation. *In the Matter of Notice of Upcoming Joint Rulemaking to Establish 2017 and Later Model Year Light Duty Vehicle GHG Emissions and CAFE Standards.* Docket ID No. EPA-HQ-OAR-0799 Docket ID No. NHTSA-2010-0131, 2011.

around for quite some time, they were a small part of the 20th-century model and played a minor role. In the introduction to this chapter, we argued that the potential transformation of the electricity system involves the movement of resources that were marginal (at best) into leading roles. The same is true of demand response, storage, and intelligent integration. They move from bit players to important supporting actors. Their impact and importance would not only come from a much larger role, but also from providing much more important functions.

> We believe that the discussion of the elements of the 21st-century electricity system belongs in a discussion of resources because they are closely intertwined and produce an effective resource, sometimes referred to as a virtual power plant.[24]

> As a UBS analysis put it:

> We note some discussion in the industry around tapping multiple revenue streams for interconnected batteries. We suspect improving

> tariffs from power markets will continue to make such compensation possible for both the DR-like attributes in reducing peak during emergency events alongside compensation for energy and ancillary benefits provided. We suspect much of this focus will eventually mesh into the wider question of Demand Response Compensation. . . .
>
> An alternative way to think of storage market penetration is effectively bidding into existing Demand response regimes.[25]

Demand response and storage have been around for decades, growing out of a need to manage peaks that became more intense as air conditioning spread. However, their 20th-century manifestation was small, slow, inconsistent, uncertain, and an afterthought. Their contemporary manifestation is quite different and widely recognized as one of the key building blocks of the 21st-century electricity model. It embodies the essential active feature of the system,[26] relying on information about the state of the network delivered on a real-time basis to technologies that can instantaneously control and match load with resources. As demand response and storage are built into the heart of the electricity system, they provide a range of functions (i.e., have a number of sources of value that are recognized in the trade[27] and academic literatures).[28]

- Demand reduction overall, and at the peak, through both reduction and load shifting.
- Avoided capital cost in generation, transmission, and distribution.
- Efficiency through reduction of line losses, reduced congestion, and transmission reinforcement.
- Ancillary services by providing reserve support for energy, standby, and balancing.
- Market structure, through support for renewables and reduced concentration of suppliers.

The circumstances of demand response are similar to those that apply to the deployment of renewable resources described above. There is readily achievable progress in the short term, and much greater potential in the long term.

> Importantly the level of DR does not have to be huge in order to realise many of the estimated benefits of this paper (e.g. 2.8% reduction in overall electricity use and a 1.3% shift in peak demand). The evidence from the literature suggests that such

reductions are achievable and that there is actually potential for electricity reductions and shifts to be much greater given the right environment.[29]

The intense interest in—and debate over—storage highlights two critical characteristics of the current development of storage technology. First, because it is important, it is attracting an immense amount of resources and entrepreneurial activity. As a result, an extremely rich technology palate of options is being created from which all the key stakeholders in the electricity space (consumers, utilities, grid operators, and policy makers) can choose.

Tesla's announcement of the opening of its book of orders for its "giga" battery factory stimulated a flood of articles about the imminent demise of the utility sector[30] and nuclear, in particular.[31] Talk of the threat of a death spiral of utilities had been in the air for several years.[32] While much of the press focused on the residential sector, UBS saw the near-term impact of storage in the commercial and industrial sectors.[33] UBS sees the commercial sector and utility-scale storage as the leading edge in the near term. As UBS put it,

> Batteries delivered at an economically competitive price are the holy grail of solar penetration, and we believe the industry will begin deploying on a large scale within the next ~5 years or less. We expect battery deployment to occur primarily where there is a clear economic rationale. One of the clearest examples is commercial scale battery deployment, which is already occurring today in several countries. Commercial customers are often subject to demand based charges, which can account for as much as half of the electric bill in some months. We think companies with differentiated battery solutions coupled with intelligent software and predictive analytics that work with the grid to avoid these charges and smooth electric demand will pave the way for mass adoption. Additionally, we expect utilities worldwide to pursue batteries on a large scale as costs drop over the next several years and renewable/intermittent generation deployments increase. Residential customers without proper pricing mechanisms in place (for example, peak demand charges) are unlikely to pursue energy storage in the short term, although we believe solar leasing companies and other energy service companies could shift towards offering batteries as part of energy packages designed to integrate more intelligently with the grid and address utility concerns around distributed generation.[34]

RMI viewed the economics in all sectors as building the potential for grid defection with residential and commercial solar PV.[35] While others also see commercial PV with storage as leading, they do not see residential all that far behind. Deutsche Bank takes a similar view. It sees grid parity in two-thirds of the U.S. states, with residential PV with storage providing over three-quarters of the demand in 5 to 10 years. Both of these analyses, which show optimism about residential solar, underscore the importance of policy that enables solar PV to enter the market on reasonable terms that reflect its value to the consumer and the electricity system.

The debate over which storage technologies will be the leading edge is instructive. It highlights that multiple storage applications and the services that they provide are available, driven by dramatically declining costs. Regardless of which among a dozen technologies take hold and which sector leads, there is no doubt that storage will play an important role in the 21st -century electricity system.[36]

Second, while much of the analysis of storage (certainly when it is tied to residential PV systems) focuses on the private costs and benefits, some have argued that there are public benefits that need to be considered.[37] These benefits include reduction in production, investment and outage costs, and improved reliability. The analysis conducted by the Brattle group for a Texas distribution utility found that the system-wide benefits constituted a significant part of the total benefit (30–40 percent)—enough to tip the scale in favor of much larger investment than would be driven by private incentives alone. Policy to capture those benefits in an effective manner and share them "fairly" is the focal point of attention in a vigorous debate over rate structure, incentives, and stranded costs.

Demand response and storage are two of the key elements in the active 21st-century electricity system. Here, it suffices to say that reducing the need for generation through intelligent management is estimated to be in the range of 10–20 percent of aggregate demand, and a higher percentage of peak demand. This should be considered a transformational dividend—an expansion of output that occurs as an external benefit or network effect that is larger than the sum of the individual elements added to the system—with respect to carbon reduction. Thus, the transformation of the electricity system has emergent characteristics that are dependent on implementing a new institutional structure. The downward pressure on peak and average prices, which has been observed in systems that are partially designed (at best) to exploit this aspect of the emerging electricity system, are an economic dividend that would be reinforced by a successful transformation of the system. Reduced overall system size will be another dividend. Thus, virtual power plants can have a substantial impact and value. At the average portfolio discussed above, a transformational dividend of 10–20 percent of demand would be equal to the sum of residential and commercial PV, tidal, wave, and hydro combined.

INSTITUTIONAL RESOURCE NEEDS

Falling costs and rising renewable load factors are the engines that presently drive change. However, as we show in Table 6.3, building a 21st-century electricity system with high levels of penetration of renewables requires substantial new physical and institutional infrastructure centered on system integration and management.[38]

Cost recovery to ensure the deployment of adequate infrastructure—a problem that plagues electricity markets in general[39]—can be compounded by the expanding role of decentralized resources with low operating costs. Incentives to innovate and compensation for intensive system management are new challenges. Open, competitive resource acquisition, economic dispatch, and net energy metering dramatically reduce the rents available to fund large, baseload construction with high capital costs. Capital outlays for new transmission assets must also be supported. The two-way, information-intensive system that allows integration and management of supply-side and demand-side resources involves an entirely different set of skills and assets that are irrelevant to fossil fuel and nuclear resources. Indeed, they replace baseload generation.

In short, the 21st-century electricity system needs new regulatory structures with more sophisticated rate structures, and business models to support active management and integration of decentralized, flexible resources. The legitimate challenges of building these institutions can be exacerbated by the opposition of powerful incumbents.

One of the main challenges and fronts in the battle for the future stems from concerns about the ability of a decentralized electricity system to meet the need for electricity in a manner that matches the reliability of the 20th-century model. In fact, building an electricity system around an intelligent network is not only a challenge that can be overcome, but also meeting that challenge yields substantial benefits beyond just maintaining reliability. The new organizational form can actually be seen as adding resources, and is a better way to meet the need for electricity in a low-carbon environment. The transformation dividend represents a significant resource (the fourth-largest after solar, wind, and efficiency, as compared to the business-as-usual central station approach of the 20th century).

Table 6.3 The Transformation Leading to the 21st-Century Electricity System

Benefits of the New 21st-Century System				
Supply				**Demand**
Distributed Generation		**System Integration**		**Efficiency**
Alternative Technologies Declining Cost Rising Load Factors Merit Order & Market Power Effects		Transmission Utility Storage Rapid Ramping Improved Forecasting	Demand Response Onsite Storage	Reduced demand Shifted demand
Policy Needs				
Open resource acquisition	True economic dispatch & net metering	Two-way intensive physical, informational infrastructure & smart grid management for integration & demand response	Cost recovery for infrastructure & management	Net metering Consumer benefits of downsizing

Source: Author.

MEETING THE NEED FOR RELIABLE ELECTRICITY IN THE 21ST CENTURY

The broader operational challenge of implementing the new system of active management with an expanding role for renewables is symbolized in a graph that depicts the load profile of the system (often referred to as the "Duck Chart" because the curves resemble the outline of a duck, as seen in the top graph of Figure 6.1). When renewables enter a grid that has been built and operated to support central station facilities and load-following peaking power, the demand for baseload power falls (the belly of the duck) in the middle of the day when the sun is shining, while the demand for peaking power rises (the head of the duck). The steep climb (ramp) from the bottom of the belly to the top of the neck, and the subsequent down ramp, are a double-edged challenge for the system.

In the upper graph of Figure 6.1, the net load to be met by nonsolar resources declines by about 17 percent as renewables are introduced. Assuming that most of that load is met by fossil fuels, this represents a major reduction in CO_2 emissions. This is a feature, not a bug. The big challenge involves meeting the slightly higher peak and, more importantly, climbing the much steeper grade to meet peak demand. The lower graph shows the changing load shape as a reduction in afternoon peak demand, with storage meeting late afternoon/early evening shoulder demand.

The solution to the steep climb (ramp) that has been offered by a number of analysts, and implemented in a number of nations, is the use of intelligent, active management to raise the duck's belly and lower its neck (see Table 6.1). NREL identifies eleven integration strategies. Lovins identifies nine measures. The Regulatory Assistance Project (RAP) identifies ten policies that can be implemented in a dynamic electricity system that actively manages supply and demand, and can lower the peak by 30 percent and dramatically increase the system-wide load factor.[40] In fact, the RAP counts "retire inflexible generating plants with high off-peak must run requirements" as a benefit to developing the integrated system of supply and demand management. Combined, the studies in Table 6.4 identify two-dozen policies. The RAP Project describes the result as follows:

> Thus, our modified post-renewable load is easier to serve than the actual load projected to exist would have been without the addition of renewable resources. This is desirable for almost any electric utility system, including those without significant renewable energy deployment issues.
>
> It's evident that the net load (including solar and wind) after application of the ten strategies is a much more uniform load to serve from dispatchable resources even with the nonsolar/wind resources

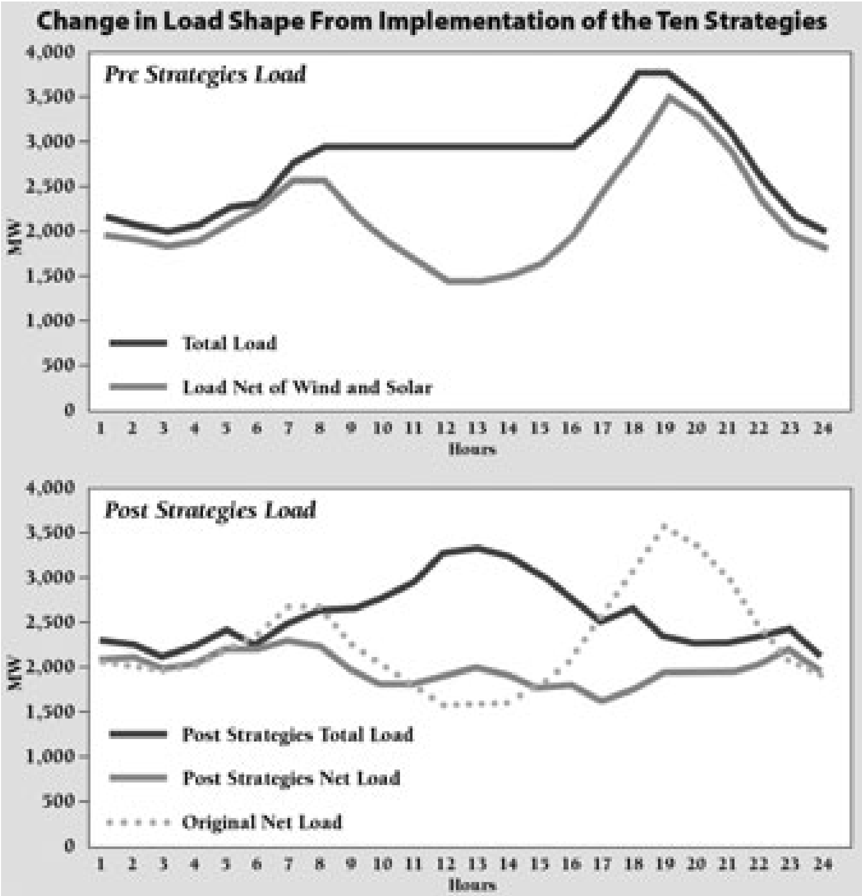


Figure 6.1 The Benefits of Actively Managing Renewable Supply and Demand

Sources: Jim Lazar, *Teaching the "Duck" to Fly,* Regulatory Assistance Project, January 2016, 8. The concept is widely used (see for example, Clean Coalition, *Flattening the Duck,* December 16, 2013; Vishal Shah and Jerimiah Booream-Phelps, *Crossing the Chasm: Solar Grid Parity in a Low Oil Price Era,* Deutsche Bank, February 27, 2015, 53; Parker et al., *Bernstein Energy & Power Blast: Equal and Opposite . . . If Solar Wins, Who Loses?* April 4, 2012, 2; Chet Lyons, *Guide to Procurement of Flexible Peaking Capacity: Energy Storage or Combustion Turbines?* Energy Strategies Group, 2014.

than the load that was forecast for this period without solar and wind. The peaks have been lowered, the troughs raised, and the utility has control over a portion of the load to schedule when it can most economically charge water heaters, air conditioners, and batteries. In essence, the effect of the ten strategies is to reduce both peaking needs and ramping requirements.[41]

Table 6.4 Measures to Manage an Intelligent, Decentralized Electricity Sector and Reduce Peak Load

Demand	System Integration
Efficiency	**Grid management**
Target efficiency to peak reduction	Expand balance area
Aggressive demand response	Improve forecasting
Manage water heater loads to reduce peak	Integrated power transactions
Smart controllers	Import/export
Rates	**Dispatchable storage**
Target fixed-cost recovery to ramping hours	Solar thermal electric with storage
Time of use rates	Utility storage in strategic locations
Supply	
Diversify renewable supply	**Distributed storage**
Geographic (particularly wind)	Community & individual storage
Technological (wind & solar)	Air conditioning water heating with storage
Target solar to peak supply (west orientation)	Electric vehicles
Re-orient conventional supply	**Deploy fast-ramp generation**
Shed inflexible baseload	

Sources: U.S. Department of Energy, *Wind Vision: A New Era for Wind Power in the United States* (Washington, DC: U.S. Government Printing Office, 2015), 90; citing Michael Milligan et al., *The Impact of Electric Industry Structure on High Wind Penetration Potential*, Technical Report NREL/TP-550-43273, NREL, July 2009, 23; E3, *Investigating a Higher Renewables Portfolio Standard in California*, Energy and Environmental Economics, Inc., January, 2015; Amory Lovins, *An Initial Critique of Dr. Charles R. Frank, Jr.'s Working Paper "The Net Benefits of Low and No-Carbon Electricity Technologies," Summarized in the Economist as "Free Exchange: Sun, Wind and Drain"* (Boulder, CO: Rocky Mountain Institute, August 7, 2014); Jim Lazar, *Teaching the "Duck" to Fly*, Regulatory Assistance Project, January 2014; Steve Nadel, "Conquering the Evening Peak," *ACEEE Blog*, November 24, 2014.

The DOE *Wind Vision* analysis argues that "wind generation variability has a minimal and manageable impact on grid reliability and related costs."[42] DOE believes that operational challenges that could arise with much higher levels of wind penetration can be easily overcome by expanding the use of techniques that have been found effective in the past. "Such challenges can be mitigated by various means including increased system flexibility, greater electric system coordination, faster dispatch schedules, improved forecasting, demand response, greater power plant cycling, and—in some cases—storage options."[43] Although the near- and mid-term challenge in resource acquisition falls far short of the elimination of all fossil fuels, the analysis of integrating much higher levels of wind and solar has progressed to detailed, utility-sponsored studies. These highlight the impact and necessity of changes to the grid,[44] and the prospect of achieving reliability that equals or exceeds current levels with the alternative approach is increasingly seen as quite good.[45]

DETAILED ANALYSIS OF CALIFORNIA

The evidence from detailed engineering studies, as well as the real world experience of advanced industrial nations, continues to mount and is now overwhelming. Penetration of wind and solar to levels far beyond what is projected (in base case U.S. Energy Information Administration [EIA] analysis of the United States, or in EPA's Clean Power Plan to reduce carbon emissions from the electricity sector) can be achieved without compromising system reliability at all. The more flexible the system is made with geographic diversity, low-cost storage, demand shaping, technological diversity, short interval scheduling, and "quick start" generation, the higher are the levels that can be achieved.

California attracts a great deal of attention because it is a large U.S. electricity market (the sixth-largest economy in the world) with a strong commitment to shifting to renewables. California is also of interest because it experienced the largest early retirement of nuclear reactors in almost two decades. In fact, it is the largest early retirement of nuclear reactors in U.S. history. The fact that it was handled with relative ease is a good indication that early retirements are manageable.

The LBNL Analyses

Lawrence Berkeley National Laboratory (LBNL) has conducted a series of analyses of increasing penetration of renewables in California. Although the analysis does not include some important potential mitigation measures, such as expanded trade over regional entities,[46] LBNL looked at a series of detailed mitigation measures and concluded that:

> Taken together, these scenarios indicate that relatively high penetrations of total VG [variable generation] can be achieved using combinations of wind and solar technologies while maintaining or even enhancing the value of the wind/solar generation compared with the value of using single wind and solar technologies in isolation.[47]

In the LBNL analysis, a "relatively high level" is a mix of wind and PV to 30–40 percent, with wind generally making a contribution that is two or three times as large as solar,[48] and central station solar with six hours of battery storage potentially adding an additional 20 percent. These levels are achieved within the constraints of maintaining the reliable operation of the system at base case levels. This conclusion is based only on an evaluation of the economic value, measured as "avoiding the capital investment cost and variable fuel and O&M costs for other (fossil-fuel-based) power plants in the power system."[49] The baseline total cost for the fossil fuel plant is $70/MWh, which is close to the "unabated" natural gas cost discussed in Chapter 5.

The LBNL analysis shows that the technical and economic processes by which policies work to mitigate the impact of variability are straight forward.

- Geographic diversity, particularly for wind, reduces extremes of generation, high or low output.[50]
- Technological diversity fosters a better fit with load.[51]
- Storage allows more energy to be captured and used when needed,[52] both by reducing curtailment[53] and by increasing demand (and therefore prices) during slack periods.[54]
- Demand shaping allows a better balance between supply and demand.[55]
- Flexibility is a key attribute, achieved by
  - sub-hourly scheduling to reduce the magnitude and impact of forecasting error,[56]
  - "quick start' generation,[57] or
  - a portfolio approach that uses a mix of generation assets that can reduce the need for flexibility of individual assets.[58]
- Exploiting the best sites for renewable resources yields much larger economic value—three times the average.[59]

The value of mitigation measures increases as the penetration of renewables increases. Figure 6.2 shows the value of renewables in the LBNL study when sites are chosen economically (the best sites first for wind and solar), and mitigation measures are adopted and implemented to maximize value.[60]

The declining "value" of renewables as penetration increases without mitigation is a common finding in these studies since production is out of sync with load. But the dramatic increase in value with mitigation is also a common finding because mitigation allows a better fit with load. Since the LBNL study gives us a flat fossil baseline, we find that a combination of 30 percent wind and 10–15 percent PV yields a value close to the flat fossil baseline. Adding CSP with six hours of storage up to 20 percent puts

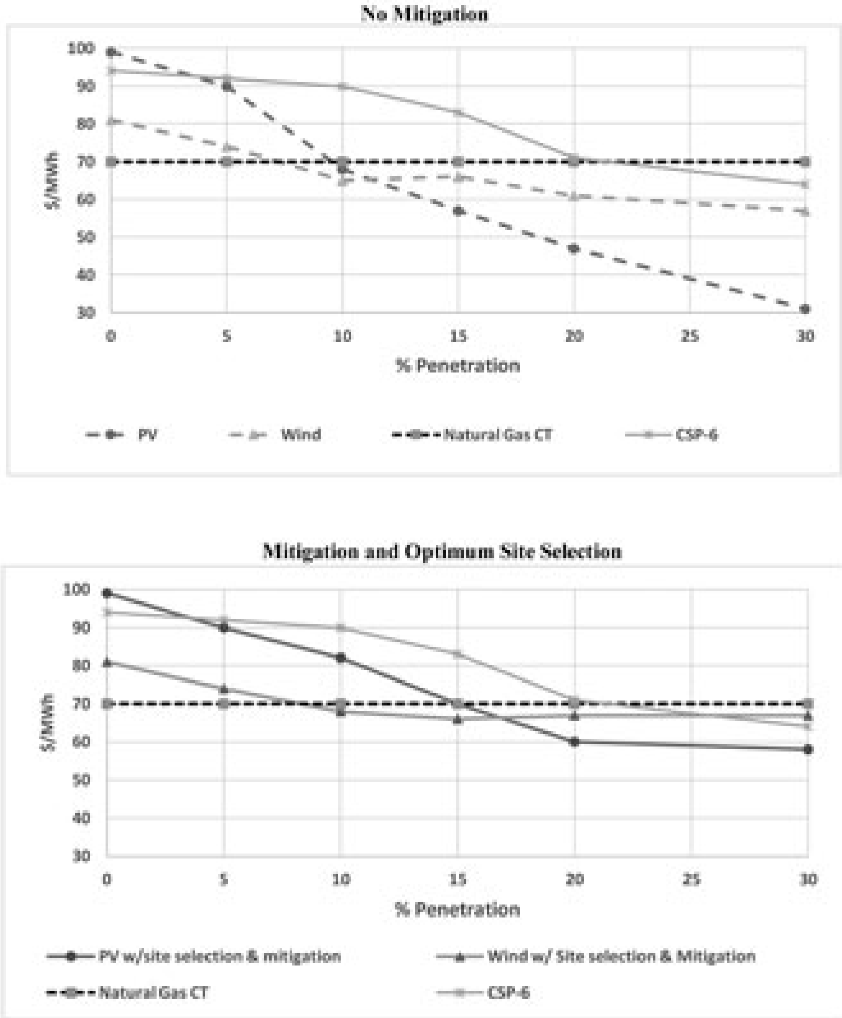


Figure 6.2 Value of Wind and PV at Various Levels of Penetration and Under Different Assumptions about Site Selection and Integration Measures

Sources: Andrew Mills and Ryan Wiser, *Changes in the Economic Value of Variable Generation at High Penetration Level: A Pilot Case Study of California*, Lawrence Berkeley National Laboratory, 2012, 7; Andrew Mills and Ryan Wiser, *Strategies for Mitigating the Reduction in Economic Value of Variable Generation with Increasing Penetration Levels*, Lawrence Berkeley National Laboratory, 2014, 3, 5, 39, 40.

renewables at almost two-thirds of total generation at a value equal to the flat fossil baseline, without reducing the value of the other renewables.

The LBNL study cautions that the choice of the level of renewable resources will depend on the relative cost of the resources. “Determining whether to pursue technological diversity as a mitigation measure would require comparing the anticipated increase in value against the potential higher cost of building combinations of technologies to achieve the target penetration level."[61] We have shown above that the current and projected costs of resources strongly favor efficiency, renewables, distributed resources, and demand management.

The LBNL analysis does "not consider many other costs and impacts that may be important, including environmental impacts, transmission and distribution costs or benefits, effects related to the "lumpiness" and irreversibility of investment decisions, and uncertainty in future fuel and investment capital costs."[62] As discussed above, the consideration of "lumpiness, irreversibility, and uncertainty" strongly favors investment in efficiency and renewables. Increases in transmission costs, which might cut against renewables, are small and offset by potential distribution cost savings. As discussed below, the empirical evidence indicates that the costs of integration are not very large.[63]

The LBNL study cautions that policy needs to be tailored to achieve some of the mitigation effects (particularly demand shaping),[64] and technology limitations need to be taken into account in system design (particularly storage).[65] The attention to specific needs, goals, and limitations stems from the fact that there are so many options that can be used to ensure reliable supply. It is not a question of whether reliability can be maintained, but rather choosing the least-cost way to do so. The costs can be quite small—far less than the resource cost difference between nuclear and the other low-carbon alternatives.[66] In the face of this evidence, claims that renewables will harm the reliability of an electricity system—one that is designed to accommodate high levels of renewables—are simply wrong. They ignore the real world and are driven entirely by politics, not scientific evidence.

California Utilities

Although the utilities in California put together an analysis that takes a very different approach than the LBNL analysis and seems much more ominous, close examination shows that when the utility analysis introduces mitigation measures, it reaches a similar end point. The utilities started with a base case of renewables at 33 percent and set up straw men of 40 percent and 50 percent PV scenarios. Not surprisingly, they find that this extreme approach produces major problems in matching supply and demand.

Consistent with the LBNL analysis, however, the introduction of mitigating policies immediately solves the problem. The utility study identifies four "least regrets opportunities," and a number of opportunities for "research and development for technologies to address over-generation."[67] Adding in three blocks of "flexibility solutions" reduces the curtailment of PV generation to the level of the 33 percent penetration, which was virtually zero. The transformation dividend is present in the utility analysis. Pursuing downward "flexibility solutions" yields 15000MW of reduced demand, which is equal to 10 percent of the capacity in the "unmitigated" PV system, and 15 percent of the capacity in the "mitigated" PV system. This is consistent with the RAP finding discussed above.

This level of "flexibility solutions" is in the range of the planning reserve—an equivalence that the literature generally notes. As the penetration of relatively small-scale distributed technologies increases, the need for planning reserves may decline because, in the current baseload approach, it is the threat of the loss of large units that drives up planning reserves. The potential for a trade-off between planning reserves and "flexibility solutions" could have a significant impact on the cost of meeting the need for electricity.

While the utility study does not model the specific "flexibility solutions," it does identify the likely primary candidates, which are the same as those modeled in the LBNL analysis. The utility study finds significant challenges, but also opportunities. The four "least regrets" opportunities identified in the study include:

- increasing regional coordination;
- pursuing a diverse portfolio of renewable resources;
- implementing a long-term, sustainable solution to address over-generation before the issue becomes more challenging; and
- implementing distributed generation solutions.

Research and development for technologies to address over-generation are plentiful, including

- promising technologies like storage (solar thermal with energy storage, pumped storage, other forms of energy storage including battery storage, electric vehicle charging, thermal energy storage) and
- flexible loads that can increase energy demand during daylight hours (advanced demand response and flexible loads).

Technical potential to implement new solutions are also available, including

- sub-five minute operations,
- creating a large potential export market for excess energy,
- changing the profile of daily energy demand, and
- optimizing the thermal generation fleet under high RPS.[68]

The high-level operational review found that operational issues appear manageable, but it is noted that several key considerations would require more detailed investigation. Overall, the transmission network would require significant expansion to transport renewable generation to customers, and significant management of the transition to 100 percent renewables.

Considerable PV generation in all four cases examined by the utilities drives demand and load pattern changes. Based on the modelled PV generation levels, the utility is likely to become winter peaking (in contrast to most regions' current summer peak), which means managing heating loads would be more critical than the current air-conditioning loads. The PV contribution levels also (typically) cause generation availability to peak around midday, so DSP would move demand into this period rather than the traditional late-night off-peak periods.[69]

OTHER STUDIES

The conclusion that high levels of penetration of renewables can be achieved without undermining reliability is supported in the literature.

- Other studies of California[70] reach the same conclusions, while simultaneously analyzing other U.S. areas.[71]
- Numerous studies of other states support the basic findings of these California studies, including very diverse areas like Texas, Mid-America,[72] and the Mid-Atlantic.[73]
- Numerous studies of other nations, particularly in Europe, come to the same conclusions.[74]
- A great deal of conceptual work is ongoing regarding how integration can be accomplished.[75]

In addition to the fact that they support the general proposition that high penetration of renewables can be achieved without undermining reliability, two important points are made in these studies.

First, the findings span different types of renewables. A study that focuses on California and MISO (the independent system operator in the Midwest) finds that policies to handle high penetration of renewables work in both cases. The only difference is that the leading renewable resources will differ between regions depending on the richness of the resource. In the upper Midwest, wind is the economically preferred option. Nevertheless, a mix of renewable resources is preferable as penetrations rise.

Second, the findings directly and indirectly support the proposition that the cost of building and operating a system that includes high penetration of renewables is quite reasonable when policies to manage the integration of renewable resources are implemented. The literature puts the cost of integration well below $10 per MWh.[76] Recalling the cost advantage that renewables enjoy today, and the even larger cost advantage that they are expected to enjoy in the mid-term, this makes the 21st-century electricity system the least-cost approach in a low-carbon environment by a wide margin.

Another particularly interesting case of a continental ecosystem is Australia. The analysis of the potential for renewables in Australia produces similar results as the United States.[77] It puts the technical potential of wind at 30 times 2011 consumption, and solar at 200–350 times 2001 consumption.[78] The estimated cost of integration is similar to the other United States and European estimates—in the range of $5 to $10/MWh, including transmission costs.[79]

The finding that the cost of the integration of distributed supply and actively managed demand are quite small enjoys a strong consensus in the literature, and is reflected in the DOE *Wind Vision*. The DOE analysis provides a simple explanation. In the early years of the transition, costs rise slightly because new generation resources are being deployed. The increasing cost of electricity is primarily the result of the need to replace aging and polluting generation with low-carbon alternatives. The new generation is more costly than the depreciated plant that had been deployed without concern about the external costs of climate change. This is consistent with the analysis offered by the EPA in its Clean Power Plan, which shows a slight increase in real costs in the mid-term.[80]

However, in the mid and long terms, costs fall. The aging, polluting generation would have needed to be replaced even without decarbonization, and the cost of the alternatives has been declining due to technological progress. In the long term, the cost of electricity is lower.

The DOE explicitly laid out the process in the case of transmission.[81] The *Wind Vision* analysis argues that transmission costs are constantly being incurred by the electricity system. In the early years, those costs are reallocated from supporting central station generation (which is shrinking) to supporting new renewable resources. There is only a slight net increase in transmission investment. As time goes on and the share of renewables grows, transmission costs increase. However, they are complementary to the deployment of renewables, whose capital and operating costs have been declining and are much lower than the nonrenewable, low-carbon alternatives.

This is consistent with our earlier analysis of resource costs. The capital cost of nuclear reactors was always high, and gets higher relative to the renewables over time. The capital cost of fossil fuel consumption increases dramatically, as carbon capture is required for decarbonization. Given the strong trends of declining cost, the savings on the capital cost of renewable resources more than offsets the increase in capital expenditures on transmission, distribution, and operation, as suggested by the *Wind Vision* scenario.

Given this conclusion, the analysis of the EPA's Clean Power Plan by the North American Electric Reliability Corporation (NERC) provides a useful link to the discussion of how the incumbent energy industries, led by nuclear, are fighting against this transformation. The NERC analysis is a classic example of the static, backward-looking industry analysis that is routinely produced in an effort to derail efforts to adopt beneficial regulations.

By making a series of unrealistic assumptions and predicting the worst possible response by industry, the NERC analysis purports to show that the Clean Power Plan is unworkable and/or will result in huge increases in cost (see Table 9.3). When it actually comes to implementing the rules, market forces and regulators overseeing the process elicit much more efficient responses. NERC purports to show that the Clean Power Plan will undermine the reliability of the electricity system.[82] Critiques of the NERC analysis show that one can only arrive at that conclusion by making erroneous assumptions about the current state of the grid, and by assuming myopic reactions from utilities, as summarized in Table 6.5.[83]

The critiques of NERC rest on many of the effective measures that have been identified in this chapter—measures that are readily available to ensure the reliability of an electricity system that features a much larger role for renewables and demand-side measures. The NERC analysis and the critiques provide a useful transition to the discussion of the attack on the 21st-century electricity system launched by nuclear power, since they invoke the same erroneous assumptions and myopic behaviors to advance their arguments.

CONCLUSION

Notwithstanding the concerns and objections of the utilities and utility-based organizations, we have shown the positive prospects for high penetration of renewables in the United States. We have noted that similar

Table 6.5 Reliability Impact of the Clean Power Plan

Weaknesses in the NERC analysis	Solutions not considered by NERC
Assumptions	
Slowing growth of renewables	Growing renewables, distributed generation to reduce transmission needs, storage
Little demand-side energy efficiency	Substantial efficiency potential in utility programs private efficiency, CHP, building codes
Myopic Utility Responses	
Bulk power only, constrained response	Excess capacity, Demand response Waivers where appropriate Alternatives Transmission: investment incentives, operational improvement, e.g. dynamic line ratings, adaptive line rating, topology control optimization Distribution: advanced metering, distribution automation, advanced management, optimization
Little flexibility	Compliance flexibility Averaging across time and space Head start Regional response Market-based strategies
Natural gas supply/delivery concerns	Natural gas market improvements Reinforced incentives for efficient operation and savings, investment in capacity
Little coal plant efficiency improvement	Fleet improvement or redispatch, cofiring with biomass, waste heat recovery, cogeneration

Sources: AEE Institute, *NERC's Clean Power Plan 'Phase I' Reliability Assessment: A Critique*, Advanced Energy Economy, May 7, 2015; Jurgen Weiss et al., *EPA's Clean Power Plan and Reliability: Assessing NERC's Initial Reliability Review*, Brattle Group, February 2015; Susan Tierney, Eric Svenson, and Brian Parsons, *Ensuring Electric Grid Reliability under the Clean Power Plan: Addressing Key Themes from the FERC Technical Conferences*, April 2015.

findings have been made for other nations. We have shown that modeling and real-world experience lead to the strong conclusion that high penetration of renewables is not only feasible, but also the least-cost approach to meeting the need for electricity in a decarbonized sector. The emerging consensus is that the current physical and institutional infrastructure can handle the growth of renewables to 30–40 percent quite well. For example, a study conducted for PJM members that included only one of the many grid management strategies (i.e., geographic diversity of renewables, which—because the resource is generally dispersed—is a natural occurrence if high levels of renewables are pursued) found that 30 percent penetration of renewables is easily manageable.[84] Half-a-dozen advanced industrial countries (Denmark, Germany, Ireland, Spain, Sweden, and Portugal) have achieved three times the current penetration of renewables as the United States.[85] A recent study for the European Commission found a 60 percent penetration of renewables to be manageable.[86] Thus, the sense of short-term crisis that utilities have sought to create (by threatening to retire several nuclear reactors) is contradicted by these findings and developments, but it feeds into and off of the larger debate about grid reliability. In fact, as more of the online reactors retire—either as planned or early—there have been no disruptions.

The analysis of this transformation has progressed greatly, and includes modeling a sector that captures the synergies of geographically diverse and widespread renewables. This, combined with key infrastructure components like expanded transmission, the tradeoff[87] with storage,[88] and demand response,[89] can help lower costs and meet demand. Moreover, the magnitude of the benefits projected in these analyses are early in the process of transformation. A wide range of opportunities is opening up that can eliminate the wall between supply and demand behind which the 20th-century baseload model was built. Doing so relies on the interrelationship of battery-powered vehicles[90] and the smart grid,[91] the Internet of things,[92] and having multiple roles for solar power.[93]

As the U.S. Department of Energy put it, concluding that wind could reach very high levels of penetration, "Wind generation variability has a minimal and manageable impact on grid reliability and related costs."[94] The potential for extremely rapid balancing, innovative battery technologies, and microgrids, which address the core problem of reliability in the digital age, have only begun to be appreciated.[95] In sum, careful analysis shows that reliability is a nonissue; the conflict is about the future of the technoeconomic structure of the electricity sector in the 21st century.

This analysis has shown that the trade and academic literature, as well as real-world experience, indicates that following a path toward a 21st-century electricity system poses no serious threat to reliability up to a 30–40 percent penetration. The literature has also identified the specific actions that can carry the system to much higher penetration of renewables. Combining the threads of this analysis, the measures that allow the system to operate at high penetration with the implementation of aggressive efficiency measures meets 80 percent of business-as-usual or base-case demand. Adding in the transformation dividend of reduced demand would put the total above 90 percent. Pursued aggressively, the magnitude and timing of the transformation meets the need for an effective response to climate change.

The conclusion is also strongly evident in looking at the least-cost penetration of renewables and their cost impact. High levels (~75 percent) yield lower cost and lower-risk, low-carbon portfolios. As a study of the potential for renewable resource in Australia concluded:

> In 2030, the lowest expected cost generation portfolio includes 60% renewable energy. Increasing the renewable proportion to 75% slightly increased expected cost (by $0.2/MWh), but significantly decreased the standard deviation of cost (representing the cost risk). Increasing the renewable proportion from the present 15% to 75% by 2030 is found to decrease expected wholesale electricity costs by $17/MWh. Fossil-fuel intensive portfolios have substantial cost risk associated with high uncertainty in future gas and carbon prices. Renewables can effectively mitigate cost risk associated with gas and carbon price uncertainty. This is found to be robust to a wide range of carbon pricing assumptions. This modelling suggests that policy mechanisms to promote an increase in renewable generation towards a level of 75% by 2030 would minimize costs to consumers, and mitigate the risk of extreme electricity prices due to uncertain gas and carbon prices.[96]
>
> Using a commercially available modelling package, PLEXOS, we model what a transition to gas fired generation in the year 2035 would deliver and compare that to a transition to power from renewable technologies. The results indicate that a transition to gas fired generation reduces emissions only marginally and that wholesale prices will be higher than the renewable energy option.[97]

This part also found that efforts to create a crisis of reliability are misguided. The electricity system is already designed to handle much larger shifts in the resource mix, or demands placed on it than the orderly development of high penetration of renewables would impose on the system. Simply put, with sensible and efficient policy, the current electricity system can easily get to much higher levels of penetration of renewables and efficiency, while the physical and institutional foundation for much higher levels is built.

The path to a low-carbon, low-pollution electricity sector is clear. The technologies are in hand. Building the physical and institutional infrastructure to support high penetration of these resources is economically justified, but that requires vigorous and swift implementation of the necessary policies. While we have identified a set of strong economic reasons to pursue the renewable/distributed/demand-based approach, as well as system management tools that can make it work, we should not underestimate the challenge of building the institutional structures that let those tools be used. As we argued in our description of progressive capitalism, the institutions are the glue that holds the system together, and they encounter the stiffest resistance from entrenched incumbents and practical obstacles.

PART IV

CHALLENGES

7

CONCEPTUALIZING MARKET IMPERFECTIONS

In the analytic framework, we argued that the activity of the state is crucial to setting economic change in motion and establishing a stable growth path once the technoeconomic paradigm emerges. The underlying forces that triggered the battle against the incumbents to institute new operating rules for the emerging 21st-century system are economic, while the battle itself is of considerable political importance.

There are also important economic challenges that must be overcome. These are dealt with in the next two chapters. Energy markets are now (and have long been) afflicted by a large number of significant market imperfections that lead those markets to perform poorly, if not fail altogether. In order to establish a stable growth path, institutional recombination must adopt policies that reduce the impact of the underlying market imperfections. In Chapter 5, we introduced this problem in terms of the need for policies throughout the diffusion lifecycle. Here, we look in detail at the underlying market imperfections through the lens of two literature reviews. Both deal with areas of energy policy that are crucial to the successful transition to a low-carbon/low-pollution system that can sustain development. In this chapter, we begin with a review of the way the market imperfections have been conceptualized (We have placed sources and citations in Appendix II). In the next chapter, we review recent empirical evidence that supports this conceptualization.

THE EFFICIENCY GAP

The Never-Ending Debate Over the Efficiency Gap

For over 30 years, economists, engineers, and policy analysts have described a phenomenon in energy markets known as the "energy paradox" or the "efficiency gap."[1] Engineering/economic analyses showed that technologies exist that could potentially reduce the energy use of consumer durables (light bulbs, air conditioners, water heaters, furnaces, building shells, and automobiles) and producer goods (motors, HVAC, and heavy-duty trucks). Several major research institutions estimate that, at present, there is a large (20–30 percent), technically feasible, economically practicable potential to reduce the energy consumption of most households, including electricity, natural gas, gasoline, and diesel.[2] The reduction in operating costs more than offsets the initial costs of the technology, resulting in substantial potential net economic benefits and the potential will grow as technology improves and learning takes place. Yet consumers do not choose to purchase the more efficient goods that result in net economic savings. Performance standards have been used to move technologies into the market.

Some have criticized the cost-benefit analysis used to support recent performance standards across a broad range of consumer durables as flawed. In particular, a great deal of attention has been placed on the recent increase in the Corporate Average Fuel Economy (café) standards that govern cars and pickup trucks (light-duty vehicles).[3] For example, perplexed by the conclusion in the EPA/National Highway Traffic Safety Administration (NHTSA) light-duty vehicle fuel economy standard analysis that "the preponderance of the estimated benefits stems from private benefits to consumers,"[4] the Mercatus Center (a market fundamentalist think tank) argued that the market cannot possibly perform this poorly with respect to energy efficiency.

> How can it be that consumers are leaving billions of potential economic gains on the table by not buying the most energy-efficient cars, clothes dryers, air conditioners, and light bulbs? Moreover, how can it also be the case that firms seeking to earn profits are likewise ignoring highly attractive opportunities to save money? If the savings are this great, why is it that a very basic labeling approach cannot remedy this seemingly stunning example of completely irrational behavior? It should be quite simple to rectify decisions that are this flawed.[5]

The Mercatus view is that, since "the preponderance of the assessed benefits is derived from an assumption of irrational consumer choice,"[6] and such behavior is easily rectified by labeling programs that already exist, "the main failure of rationality is that of the regulators themselves."[7] In their view, the fault lies with the agencies, whose analysis must be wrong because it was prepared under legal mandates structured so that "government officials act as if they are guided by a single mission myopia that leads to the exclusion of all concerns other than their agency's mandate."[8]

The correct answer to the paradox is well-known. Energy markets are imperfect—riddled with barriers and obstacles to efficiency—and the market for electricity is no exception. Market imperfections lead to market failures and underinvestment in energy-saving technologies. McKinsey & Company offered the following framing in one of a series of analyses addressing various aspects of the ongoing transformation of the electricity sector.

> The highly compelling nature of energy efficiency raises the question of why the economy has not already captured this potential, since it is so large and attractive. In fact, much progress has been made over the past few decades throughout the U.S., with even greater results in select regions and applications. Since 1980, energy consumption per unit of floor space has decreased 11 percent in residential and 21 percent in commercial sectors, while industrial energy consumption per real dollar of GDP output has decreased 41 percent. As impressive as the gains have been, however, an even greater potential remains due to multiple and persistent barriers present at both the individual opportunity level and overall system level. By their nature, energy efficiency measures typically require a substantial upfront investment in exchange for savings that accrue over the lifetime of the deployed measures. Additionally, efficiency potential is highly fragmented, spread across more than 100 million locations and billions of devices used in residential, commercial, and industrial settings. This dispersion ensures that efficiency is the highest priority for virtually no one. Finally, measuring and verifying energy not consumed is by its nature difficult. Fundamentally, these attributes of energy efficiency give rise to specific barriers that require opportunity-specific solution strategies and suggest components of an overarching strategy.[9]

Even in the industrial sector, where firms are considered to be motivated primarily by economic profitability incentives, the efficiency gap is evident. A review of 160 studies of industrial energy efficiency investments conducted for the United Nations Industrial Development

Organization (UNIDO) framed the analytic issues by posing and answering the key questions as follows:

> Why do organizations impose very stringent investment criteria for projects to improve energy efficiency?
>
> Why do organizations neglect projects that appear to meet these criteria?
>
> Why do organizations neglect energy efficient and apparently cost-effective alternatives when making broader investment, operational, maintenance and purchasing decisions?[10]
>
> Because of barriers to energy efficiency these seemingly profitable measures are not being adopted. . . . There is a large body of literature on the nature of barriers to energy efficiency at the micro and the macro level, which draws on partly overlapping concepts from *neo-classical economics*, *institutional economics* (including principal-agent theory and transaction cost economics), *behavioral economics*, psychology and sociology. Barriers at the macro level involve price distortions or institutional failures. In comparison, the literature on barriers at the micro level tries to explain why organizations fail to invest in energy efficiency even though it appears to be profitable under current economic conditions determined at the macro level.[11]

The Mercatus critique of the efficiency gap concept embodies a second flaw that efficiency gap analysts have overcome in the past decade—defining the problem as solely a consumer information problem. In fact, over the last ten years, the important role that market imperfections play on the supply-side of the market has been noted. The market outcome reflects both the supply of and demand for technologies. As Carl Blumstein notes:

> But what if the energy-efficiency gap was regularly framed as a *supply-side* problem, such as a concern about whether problems in the *supply-chain* create a gap between the energy-efficiency potential of goods and services and the adoption of energy-efficient goods and services? After all, in many instances consumer choices are constrained because it is not practical for manufacturers to produce a continuum of choices; suppliers can only provide a limited set of discrete choices within a range of prices, functionality, and energy efficiency. In addition, even when the choice set of energy users is not constrained, limitations related to the behavior of actors in the supply chain may restrict consumer choices.[12]

When market barriers and imperfections on the supply and demand sides of the energy market are properly comprehended, it is clear that the performance standards are not an example of "overriding consumer preferences with energy regulations"[13] based on an assumption of consumer irrationality, as Mercatus claims. Rather, even without significant externalities (like climate change), energy performance standards are a well-justified effort to overcome severe market obstacles, constraints, and cognitive limitations on human decision making that impose huge, unnecessary energy costs on consumers and the economy.

COMPREHENSIVE EXPLANATIONS OF THE EFFICIENCY GAP

This chapter presents a comprehensive analytic framework that explains the energy efficiency gap by examining several other frameworks that have been developed over the past two decades. Given that the literature reviews involve a large number of sources, we present summary tables in the text and annotated versions of the tables in the appendix. These frameworks rest upon a strong foundation of empirical analysis that has been developed over more than a quarter-century and strengthened considerably in the past decade.

Lawrence Berkeley National Laboratory (LBNL)

Table 7.1 summarizes three major conceptual efforts to analyze the efficiency gap. A 1996 paper prepared by analysts at LBNL[14] framed the analysis in terms of the role of policy intervention to promote efficiency as states restructured the electricity market. The paper "focuses on understanding to what extent some form of future intervention may be warranted and how we might judge the success of particular interventions."[15]

The LBNL effort was motivated by the launch of electricity market restructuring in the mid 1990s, since the shift to greater reliance on the market raised questions about whether the efficiency gap would grow, if policies to promote efficiency were cut back. While restructuring did not spread throughout the utility industry, reliance on interventions in the market to increase efficiency and renewables has grown in the past few years, even in the deregulated states.[16] The growth of market interventions is consistent with the conclusions in the LBNL paper. "We conclude that there are compelling justifications for future energy-efficiency policies. Nevertheless, in order to succeed, they must be based on a sound understanding of the market problems they seek to correct and a realistic assessment of their likely efficacy."[17]

Table 7.1 Conceptual Frameworks for Identifying Market Barriers

LBNL Market Barriers to Energy Efficiency

Barriers[1]	**Market Failures**	**Transaction Cost**[2]	**Behavioral factors**[16]
Misplaced Incentives Agency[4]	Externalities	Sunk Costs[3]	Custom[17]
	Mispricing[20]	Lifetime[5]	Values[18] & Commitment[19]
Capital Illiquidity[8]	Public Goods[22]	Risk[6] & Uncertainty[7]	Social Group & Status[21]
Bundling	Basic Research[23]	Asymmetric Info.[9]	Psychological Prospect[24]
Multi-Attribute	Information	Imperfect Info.[10]	Ability to Process Info[27]
Gold Plating[11]	Appropriability[25]	Cost[12]	Bounded Rationality[26]
Inseparability[13]	Imperfect Competition/Market Power[28]	Search[15]	
Regulation Price Distortion[14]		Bargaining Cost[29]	
Chain of Barriers Disaggregated Mkt.[15]			

Resource for the Future Market and Behavioral Failures Relevant to Energy Efficiency

Societal Failures	**Structural Failures**	**Potential Behavioral Failures**[11]
Energy Market Failures	Capital Market Failures	Prospect Theory[12]
Environmental Externalities[1]	Liquidity Constraints[5]	Bounded Rationality[13]
Energy Security	Information Problems[6]	Heuristic Decision Making[14]
Innovation Market Failures	Lack of Information[7]	Information[15]
Research & Development Spillovers[2]	Asymmetric Info.	
Learning-by-Doing Spillovers[3]	Adverse Selection[8]	
Learning-by-Using[4]	Principal-Agent Problems[9]	
	Average-Cost Electricity Pricing[10]	

Barriers to Industrial Energy Efficiency

Schools of Thought	Orthodox Economics Economics of What?	Agency Theory & Economics Information	Transaction Cost Economics	Behavioral
Imperfections	Risk (1) Access to Capital (2) Routine (10)	Split Incentives (3) Imperfect (4) Asymmetric Information (5) Hidden Costs (7)	Adverse Selection (6)	Inertia/Status Quo Bias (9) Bounded Rationality (8)

Source and citation: See Appendix II for sources and notes.

As shown in Table 7.1, the LBNL paper by Golove and Eto[18] identifies four broad categories of factors that inhibited investments in energy efficiency: barriers, transactions costs, market failures, and behavioral (noneconomic) factors. It identifies about two-dozen specific factors spread roughly equally across these four categories. A key aspect of the analysis is to identify each of the categories as coming from a different tradition in the economic literature. The barriers category is made up of market structural factors. The market failure category is made up of externalities and imperfect competition. However, the LBNL paper bases a substantial part of its argument on a transaction cost perspective as a critique of neoclassical economics.

> Neo-classical economics generally relies on the assumption of frictionless transactions in which no costs are associated with the transaction itself. In other words, the cost of activities such as collecting and analyzing information; negotiating with potential suppliers, partners and customers; and risk are assumed to be nonexistent or insignificant. This assumption has been increasingly challenged in recent years. The insights developed through these challenges represent an important way to evaluate aspects of various market failures (especially those associated with imperfect information).[19]

Starting from the observation that "transaction costs are not insignificant but, in fact, constitute a primary explanation for the particular form taken by many economic institutions and contractual relations,"[20] the LBNL paper identifies such costs and information as critical issues, pointing out that "the key issue surrounding information is not its public goods character, but rather its asymmetric distribution combined with the tendency of those who have it to use it opportunistically."[21]

Resources for the Future

A more recent paper from Resources for the Future (RFF), entitled *Energy Efficiency Economics and Policy,* is summarized in the middle of Table 7.1. It addresses exactly the same issues as the earlier LBNL paper—the debate over the efficiency gap observed in energy markets. Using the investment framework, the authors of the RFF paper characterize the efficiency gap debate as follows:

> Much of the literature on energy efficiency focuses on elucidating the potential rationales for policy intervention and evaluating the effectiveness and cost of such interventions in practice. Within this

> literature there is a long-standing debate surrounding the commonly cited "energy efficiency gap." . . . Within the investment framework . . . the energy efficiency gap takes the form of under investment in energy efficiency relative to a description of the socially optimal level of energy efficiency. Such under investment is also sometimes described as an observed rate or probability of adoption of energy-efficient technologies that is "too slow."[22]

The RFF paper suggests three broad categories of market failures—the individual, the interaction between economic agents, and the fit between economic agents and society. We refer to these three levels as the behavioral, the market structural, and the societal levels. In the present context, we consider behavioral failures to represent consumer behavior that is inconsistent with utility maximization, or in the current context, energy service cost-minimization. In contrast, market failure analysis is distinct in presupposing individual rationality and focusing on the conditions surrounding interactions among economic agents and society.[23]

The societal-level market failures are closest to what traditional sources of the economic literature refer to as market failure. These are primarily externalities and public goods. In the market failure category, the table shows the distinction between the structural and societal levels suggested by the paper. It also includes a few more specific failures that were discussed in the text, but not included in the original table. There are about a dozen specific market failures spread across these categories. These were also considered market failures in the LBNL framework. The LBNL barriers and transaction costs fit in the category of interactions between economic agents, as would imperfect competition.

One obvious point is that, as in the case of the LBNL framework, information problems occur in all categories of the RFF analysis, with several manifestations in each. Also note that RFF ties the investment framework to the innovation adoption framework. In this analysis, I do so through the analysis of market imperfections.

United Nations Industrial Development Organization (UNIDO)

The bottom of Table 7.1 summarizes a comprehensive review of the causes of the efficiency gap in industrial sectors across the globe. It is based on a conceptualization and analysis prepared for the United Nations Industrial Development Organization (UNIDO) by analysts at universities in the United Kingdom. It is based on a review of over 160 studies of barriers to energy efficiency in industrial enterprises.

It can be argued that the analysis of industrial sectors provides the most compelling evidence that an energy efficiency gap exists, since these are contexts in which the incentive to adopt economically rational technologies should be strong (if not pure), and the knowledge and ability to evaluate alternatives should be greater than society at large. Moreover, since energy is a cost of doing business, records and data should be superior to the residential sector, so evaluation and calculation should be better. In spite of these factors pointing toward economic rationality, and notwithstanding assumptions of motivation and capability, these authors find solid empirical evidence that the efficiency gap exists.

As was the case in the LBNL analysis, the UNIDO analysis identified a school of economic thought that can be closely associated with each of the categories of market barriers and imperfections. The broad categories in the UNIDO analysis match up well with the perspectives offered by LBNL and RFF, plus an additional externalities category.

Other Frameworks

The first part of Table 7.2 summarizes a framework proposed by the California Energy Institute. It is notable in two respects. First, it is oriented toward businesses, which is a useful antidote to the overemphasis on residential consumers in the efficiency gap debate. Second, it explicitly endeavors to summarize and compile the various approaches to analyzing the "efficiency gap" used by others. In doing so, it returns to the traditional distinction that is made between market failures, which are recognized in neoclassical approaches, and other obstacles to investment in energy efficiency in the market. It identifies two other broad categories—market barriers and noneconomic factors. The California Energy Institute also devotes a great deal of attention to behavioral factors.

Table 7.2 Behavioral Factors

Behavior Assumptions Underlying Energy Efficiency Programs For Businesses

<u>Neo Classical Economics</u>

Explanations for the gap:

1. The gap is illusory
2. There are hidden or unaccounted for costs of energy efficiency investments
3. Consumer markets are heterogeneous
4. High discount rates assigned to energy efficiency investments resulting from perceived risk

5. Conditions that are known to cause market failure:
    1. externalities
    2. public goods
    3. imperfect information
    4. imperfect competition

Market Barriers

1. Situations involving Misplaced or Split Incentives (also called agency problems)
2. Limited Availability of Capital,
3. Market Power
4. Regulatory Distortions
5. Transaction Costs
6. Inseparability of energy efficiency features from other desirable or undesirable product features

Non-Economic Explanations

1. Rationality is only one of several decision-making heuristics that may be applied in a given decision-making situation.
2. Decision makers employ varying decision-making heuristics depending on the situation.
3. Decision-making units are often not individuals.
4. Decisions made by organizations are affected by a wide variety of social processes and heavily influenced by the behaviors of their leaders.
5. Organizational Influences: Authority, Size, Hierarchy of needs (1. Health and Safety Requirements, 2. Regulatory Compliance, 3. Corporate Improvement Initiatives, 4. Maintenance) 5. Productivity, 6. Importance of Energy Efficiency to Profitability); Management policy(1. Whether the organization has annual energy efficiency goals. 2. Whether reserves and budgets are established for funding energy efficiency investments. 3. Whether hurdle rates for energy efficiency investments are high or low. 4. The review process that is to be used to evaluate energy efficiency improvements. 5. Who is responsible for "managing" the company's energy efficiency program).

Edward Vine, 2009, *Behavior Assumptions Underlying Energy Efficiency Programs For Businesses*, California Institute for Energy and Environment, January.

General Behavioral Economic Analysis

Motivation:	Foundations: Values, Attitudes, Preferences and Choice Advanced: Fairness, Social Preferences
Influence:	Foundations: Reference Points, Nature and Measurement of Utility Advanced: Signaling, Learning

(*Continued*)

Table 7.2 (Continued)

Perception:	Foundations: Decision-making under Risk and Uncertainty, Utility Theory Prospect Theory, Loss Aversion, Decision Weighting Advanced: Behavioral Game Theory, Bargaining
Calculation:	Foundations: Mental Accounting, Framing and Editing, Budgeting and Fungibility, Choice Bracketing Advanced: The Discounted Utility Model, Alternative Intertemporal Choice

Nick Wilkinson, *An Introduction to Behavioral Economics*, New York: Palgrave, 2008.

The second part of Table 7.2 highlights the importance of behavioral economics. Several analyses have emphasized consideration of behavioral factors.[24] In this approach, many of the structural, endemic, and transaction cost/institutional factors are identified as filtering through the behavioral determinants of action to produce the outcome observed in the market. The findings of behavioral economics can be usefully divided into four categories (motivation, influence, perception, and calculation) and described at two levels (foundational and advanced).[25]

Another comprehensive approach that adds depth to the analysis is the framework offered in a detailed analysis of efficiency in the building sector, prepared by McKinsey & Company (see Table 7.3). The McKinsey conceptualization of barriers and obstacles to energy efficiency uses three broad categories—structural, behavioral, and availability. About two

Table 7.3 McKinsey & Company Market Barriers to Home Energy Efficiency

KcKinsey Category	McKinsey Nature	McKinsey Description	Cluster
Behavioral	Awareness	Low priority, Preference for other attributes	CD, RLA
Availability	Availability	Restricted procurement, 1st cost focus	CD
Behavioral	Awareness	Shop for price and features	RD
Behavioral	Awareness	Limited understanding of use and savings	CEPB, EH, GB, RLA
Behavioral	Custom & Habit	Little attention at time of sale	NH
Behavioral	Custom & Habit	Underestimation of plug load	RD

Behavioral	Custom & Habit	Aversion to change	CI
Behavioral	Custom & Habit	CFLS perceived as inferior	RLA
Behavioral	Hurdle	Payback-Hurdle, 28% discount rate	CEPB
Behavioral	Hurdle	Payback-Hurdle, 40% discount rate	EH
Behavioral	Use	Improper use and maintenance	CEPB, EH, RD
Behavioral	Awareness	Not accountable for efficiency	CI
Availability	Capital	Competing use of capital	EH, GB, RLA, CI
Structural	Agency	Tenant pays, builder ignores	CEPB, EH, RD
Availability	Availability	Lack of contractors	EH
Availability	Availability	Lack of availability in area	NH
Availability	Availability	Lack of demand => lack of R&D	RD
Availability	Availability	Emergency replacement	RLA
Availability	Bundling	Efficiency bundled with other features	RLA
Structural	Owner Transfer	Lack of premium at time of sale	CD, NH, NPB, RLA
Structural	Owner Transfer	Limits payback to occupancy period	EH
Structural	Transaction	Lack of information	NPB
Structural	Transaction	Disruption during improvement process	EH
Structural	Transaction	Difficult to identify efficient devices	RD
Behavioral	Risk/Uncertainty	Business failure risk	CEPB
Behavioral	Risk/Uncertainty	Lack of reliability	CI
Structural	Transaction	Research, procurement and preparation	EH, GB, RLA

Source: McKinsey & Company, "Unlocking Energy Efficiency in the U.S. Economy," *McKinsey.com*, 2009; Tables 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, Exhibits 14, 15, 16, 19, 21, 24, 26, 27, 29, 30.

dozen specific barriers are described. Moreover, McKinsey identifies nine different clusters of activity in the building sector. The manifestation of the barriers is different in the clusters, so McKinsey ends up with fifty discrete barriers.

THE CLIMATE CHANGE LITERATURE

The climate change literature has squarely confronted the problem of market barriers and imperfections that affect innovation and diffusion of new technologies. In order to induce rapid change in economic activities, policy must overcome the inertia created by established investment and behavior patterns built up over decades. The set of factors that underlie the inertia to respond to climate change are similar to—and magnify—the market barriers and imperfections that underlie the efficiency gap. The literature advocates for targeted innovations and induced technological change.

Over the course of the last decade, climate change analysis has focused on the extent to which market processes (through the reaction to price increases) can be relied upon, and where policies that seek to direct, target, and accelerate technological innovation and diffusion are needed. Thus, the debate among economists grappling with the analysis of climate change replicates and parallels the efficiency gap debate. The conceptual and empirical analysis of climate change adds a great deal of evidence to reinforce the conclusions about the barriers and imperfections that affect energy markets. Because the potential external costs are so large, climate change puts a spotlight on technological innovation. The growing concern over adjustment of the economy leads to concern over an "innovation gap."[26]

Because decarbonization is such a large commitment, placing the decision to decarbonize in a broader historical context provides an important perspective to help appreciate both the challenge and the opportunity. The existing structure of resources centered on fossil fuels has been in place for a long period and has a great deal of inertia on its side. Change is being dictated by decarbonization policy. Without policies to break the inertia of fossil fuels, change will not come about (or will be slower and more costly).

If the only barrier to an efficient response to the end of the implicit subsidy for fossil fuels was the internalization of the cost of carbon, policy makers could just impose a substantial tax on carbon and let the marketplace work. Unfortunately, that simple approach would not be as effective as hoped because, as we have seen, the electricity market is plagued by other significant market barriers and imperfections. Many of the market barriers and imperfections identified in the efficiency gap literature afflict the transition away from fossil fuels, and are magnified by two centuries of inertia behind fossil fuels.[27] The challenge of climate change magnifies the importance of those barriers; it does not eliminate them.

Comprehensive Analytic Frameworks

Table 7.4 combines the market barriers and imperfections frameworks from comprehensive frameworks offered by analysts at Imperial College, Resources for the Future (RFF), and Oak Ridge National Laboratory (Oak Ridge). The RFF analysis tends to emphasize the more traditional barriers—externalities, market structure, and transaction costs.

The analysis conducted by Oak Ridge was in response to a congressionally mandated "report describing barriers to GHG [greenhouse gas] intensity reducing technologies. It covers 15 technologies that would affect four goals: "reducing emissions from energy end use and infrastructure, reducing emissions from energy supply, capturing and sequestering carbon dioxide, and reducing emissions of non-CO_2 GHGs."

The Oak Ridge document refers to an "Iron Triangle of Barriers," defined by "Incumbent Support," "Transaction Costs," and "Business Innovation Risk." In fact, it is really an "Iron Parallelogram," with the fourth side representing unfavorable and uncertain policy in a number of areas. The Oak Ridge analysis also highlights the power of incumbents, which is identified as an important barrier throughout the climate change literature. Combined, the RFF and Oak Ridge frameworks incorporate all of the factors included in the Imperial College framework.

Rejection of Price Fundamentalism

An exchange in *Energy Economics* provides background, as well as a direct link from the climate change debate to the central issue of the market imperfection/barrier framework through the problem of pricing carbon. It was set up as a debate between William Nordhaus and Jon Weyant, who offered contrasting points of view, with Roger Noll commenting.

Nordaus' defense of what he calls the "price fundamentalism" approach to climate change analysis and policymaking concedes a long list of exceptions to "price fundamentalism"—exceptions considered extremely important by a growing number of energy analysts.

> Getting the price of carbon right is fundamentally important for stimulating innovations in technologies to mitigate global warming. The major necessary condition for ensuring that climate friendly innovation occurs is that the price of carbon is sufficiently high. . . . Under very limited conditions, setting carbon prices to reflect the

Table 7.4 Market Barriers and Imperfections in Climate Change Analysis

Traditional	Resources for the Future	Oak Ridge	Imperial College
Knowledge Externality	Knowledge externalities not captured by markets Research and development Importance of learning by searching Deployment: Importance of learning by doing Network effects, returns to scale		Innovation investment gap saving opportunities exploited Learning by searching Learning by doing Network effects
Market Structure	Long investment cycles, increasing returns, Network effects Monopolistic structures hinders innovation Undifferentiated product	High upfront costs Monopoly power Undifferentiated product	Entry barriers Cost structure Monopolistic
Transaction Cost & New Institutional	Information: Value of information Uncertainty: As a cause of underinvestment High risk premia on new technologies Sunk costs and embedded infrastructure	Imperfect and misinformation Lack of specialized info & validation Risk, technical, marketplace business	Information Uncertainty New technology risk premia Sunk cost in infrastructure
Endemic	Perverse Incentives Principle agent Challenge of creating new markets	Short-term view Misplaced Incentives Inadequate supply chain	Asymmetric information Agency problem
Behavior	Sluggish demand response Agency problem First cost sensitivity Calculation difficulties		

Political Power & Policy	Lack of leadership Carbon tax level and permanence Statutory Regulatory risk Fiscal policy Inertia & its cost of Inertia	Unfavorable & unfriendly regulation, Unfavorable & unfriendly fiscal policy Support for incumbent industry structure	Uncertainty due to political economy of unstable commitment to policy Difficult to price due to ambiguous long-term value Slow response adds decades to transition & increases adjustment costs substantially

Source: Resources for the Future: Raymond J. Kopp et al., *Assessing U.S. Climate Policy Options* (Washington, D.C.: Resources for the Future, November 2007); Oak Ridge: Marilyn A. Brown et al., *Carbon Lock-In: Barriers to Deploying Climate Mitigation Technologies* (Oak Ridge, TN: Oak Ridge National Laboratory, January 2008); Imperial College: Robert Gross et al., *On Picking Winners: The Need for Targeted Support for Renewable Energy* (London: Imperial College, October 2012); Yong Liu, "Barriers to the Adoption of Low Carbon Production: A Multiple-Case Study of Chinese Industrial Firms," *Energy Policy* 67 (2014).

> damages from carbon emission is also a sufficient condition for the appropriate innovation to be undertaken in market-oriented sectors. This conclusion, which I have labeled "price fundamentalism," must be qualified if the price is wrong and for those parts of research that are not profit-driven (particularly basic research), and when energy investments have particular burdens such as networking or large scale. . . .
>
> If the environmental externality is mispriced, the marginal social return to green investment will be misaligned with those in normal industries. . . .
>
> Technology policy may not optimally internalize the innovation spillovers. This may occur because appropriability differs across sectors and technologies and perhaps even within technologies. It is clear that appropriability is low for fundamental research. Some economists believe that appropriability is low for process (as opposed to product) innovations, transparent (as opposed to easily hidden) innovations, administrative or institutional (as opposed to production) innovations, and networked (as opposed to stand-alone) innovations. . . .
>
> A final important qualification is that this analysis applies primarily to research that is profit-oriented. . . . One issue involves sectors that have a substantial component of not-for-profit research. . . . A second important question is where government should draw the line between areas that are viewed as appropriate for not-for-profit support and those that are governed by the market.

Most other possible qualifications turn out to be specific applications of one of the first three.

> [Qualification 1:] . . . Energy production has many other externalities. . . . Energy technology has a particularly global dimension.
>
> [Qualification 2:] . . . Green innovations have important network characteristics. . . . Green innovations require especially large investments (or involve a large component of basic research, or have great inertia). . . . Outcomes of energy research are highly uncertain.[28]

What Nordhaus calls "qualifications" are frequently called "market imperfections" or "barriers." Weyant starts with the R&D imperfection.

> This lack of "appropriability" of the benefits of one's own innovation creates a strong motivation for public support of R&D. Such support

> augments the extent to which simply increasing the price of clean energy relative to that of dirty energy induces innovation. A number of studies . . . estimate the social rate of return for innovation expenditures at approximately double the rate of return on private R&D expenditures. . . . A close look at the energy sector industries and their potential entrants leads to the conclusion that they are industries where appropriability is difficult.[29]

However, Weyant elaborates on—and goes well beyond—the list of qualifications offered by Nordhaus. He sees several additional supply-side problems.

> A close look at the energy industries and their potential entrants leads to the conclusion that . . . entry is risky and expensive, market organization is more likely to be oligopolistic than perfectly competitive, and information is strategically held and difficult to obtain. . . .
>
> Further complicating matters, existing companies in energy-related industries—those that produce energy, those that manufacture the equipment that produces, converts and uses energy, and those that distribute energy—can have substantial incentives to delay the introduction of new technologies. This can happen if their current technologies are more profitable than the new ones that might be (or have been) invented, or if they are in explicitly (oil and gas) or implicitly (electric generation equipment producers and automakers) oligopolistic structured, or if they are imperfectly regulated (electric and gas utilities). The incentive arises partly because the infrastructure for producing, distributing, and promoting the industries' current products require large investments that have already been incurred.[30]

He also looks beyond the early phases of research and development that Nordhaus focuses on, noting market imperfections that may retard the adoption and diffusion of technologies on the demand-side.

> Imperfections in the market for energy-converting and energy-consuming equipment may be impeding the rate of diffusion of new technologies that are already economically competitive and welfare improving. This situation can result for several different types of market failure, including poor or asymmetric information available to purchasers, limits on individual's ability to make rational decisions because of time or skill constraints, principal-agent incongruities

> between building owners and building residents, and lack of financing opportunities.[31]

Roger Noll looks at the contrasting views and concludes, "Superficially, these messages conflict, but both are offered with sufficient caveats that, with minor amendments, these articles provide the right approach to near-term U.S. climate policy. Here we elaborate on the amendments that integrate these articles."[32] His amendments add important considerations that further complicate the terrain of policymaking.

> In principle, one could impose taxes on GHG emissions that correct for information imperfection, coordination failures, and market concentration, but the financial cost to consumers of using price instruments to overcome these problems plausibly could be too high to be politically feasible and higher than the cost of simply subsidizing green energy R&D. . . .
>
> In the absence of targeted government interventions utilities are unlikely to make socially optimal investments in these technologies simply on the basis of an optimal emissions tax and a general R&D subsidy . . . potential entrants face a problem that, for the foreseeable future, the infrastructure is . . . a complement as well as a substitute. . . . Thus, efficient diffusion of new green technologies requires involving the incumbents.[33]

Noll cautions that "the key question is how much delay is the commercialization of new green technologies likely to occur even if Pigovian taxes and subsidies are imposed. The answer to this question remains unclear." While the available answer is not precise, the evidence suggests that the cost of inertia is quite large, and targeted approaches lower costs and speed the transition.[34]

THE EMPIRICAL EVIDENCE OF MARKET IMPERFECTIONS

The empirical evidence that supports the conceptualization of market barriers and imperfections underlying the efficiency gap and the climate change literatures are identified in Table 7.5 with the citations provided in the Appendix to this chapter. The framework used in Table 7.5 reconciles the diversity of the literature reviewed, identifying five schools of analysis: (1) traditional neoclassical and industrial organization (2) transaction costs/new institution economics (3) behavioral economics, (4) endemic flaws, and (5) political power and policy.

Table 7.5 Recent Empirical Evidence of Market Imperfections in Relevant Literature

Schools of Thought/ Imperfection	Efficiency	Climate
Traditional		
Externalities		
Public Goods & Bads	28, 55, a, b	24,132, 177, 197, ZL
Basic Research/Stock of Knowledge		46, 37, N
Network Effects	127, ak	82, 134, I, K
Learning-by-Doing & Using	47, i	134, 105,120, 153, E
Localization		101, 153, 182, H
Industry Structure	122, 127, 163, 167	
Imperfect Competition		
Concentration	16, m	
Barriers to Entry		
Scale	39, r	151, G
Cost structure		44, 106, 134, I
Switching costs	165, t	
Technology	136, w	
R&D		90, 143, 15, E
Investment		
Marketing		
Bundling: Multi-attribute	162, 21, 116, z	
Cost-Price		
Limit impact of price	74, 116, ac	
Sluggish Demand/Fragmented MKT.		82, 97, 110, W
Limited payback	74, 165, ae	
Behavioral	117,133,144,149,159,173	
Motivation & Values	7, 6, h	39, ZM
Non-economic	4	
Influence & Commitment		
Custom	145, 146	
Social group & status	6, h	97, ZN
Perception	13, al	
Bounded Vision/Attention	1,162, k	
Prospect/Risk Aversion	151,165, l	
Calculation		77, 78 8, Z
Bounded rationality	10, 75, d, o	

(*Continued*)

Table 7.5 (Continued)

Schools of Thought/ Imperfection	Efficiency	Climate
Limited ability to process info	4, q	
Heuristic decision making	95, s	
Discounting difficulty	47, 95, 96, 113, 136, v	
Transaction Cost/Institutional		
Search and Information	88, 108	
Imperfect information	10, 100, n	19, 62, 90, U
Availability	10, 185, d	
Accuracy		
Search cost	41, 185, u	
Bargaining		
Risk & Uncertainty	32, 33, 165, t	42, 83, 103, 180, 188, R
Liability		
Enforcement		
Fuel Price		82, 134
Sunk costs		83
Hidden cost	185, ab	106
High Risk Premia		106, T
Incomplete Markets		82, 97, 179
Endemic Imperfections		
Asymmetric Info		
Agency	72, 163, 185, c, ad	83, 193, Q
Adverse selection	41, e	79, 44, X
Perverse incentives	167, f	
Lack of capital		
Political Power & Policy		
Monopoly/lack of competition		101, 155, 187, 188, ZB
Incumbent power		182, ZA
Institutional support	167, af	
Inertia	136, ag	83, 1, 69, 106, M, V
Regulation		
Price	41, 88, 121, ah	
Aggregate, Avg.-cost	95, ai	
Allocating fuel price volatility		82, 98, 203, O
Permitting		
Lack of commitment	108, aj	83, 110, 156, 181

Sources: See Appendix II for sources and notes.

THE EFFICIENCY GAP

The climate change literature is the primary focus of this book, but several observations on the efficiency gap are informative as a starting point. The most frequent studies present real-world evidence of how the barriers operate to reduce investment in energy-saving technologies. A second type of study seeks to evaluate the impact of policies to reduce the efficiency gap. Since there is a great deal of overlap between the efficiency gap literature and the climate change literature, we will discuss the imperfections of greatest importance in relation to climate change.

A particular target of this analysis, as suggested by the Mercatus reaction to fuel economy rules, is performance standards. When done properly, performance standards are a particularly effective approach in a capitalist economy. While the standard sets a target level of energy consumption (or pollution reduction), it does not dictate which technology must be used. Companies are free to select the approach that best suits them, which makes well-designed performance standards a form of regulation that is "command but not control." The logic of "command but not control" regulation is fairly simple. Set a reasonably aggressive and progressive standard and allow the manufacturers of the energy-consuming equipment find the least-cost way to achieve the goal.

The engineering-economic analysis indicates that, although the standards may increase the cost of the consumer durable, the reduction in energy expenditures is larger, resulting in a net benefit to consumers. We have also pointed to evidence that the cost of energy-saving technologies tends to be smaller than the *ex ante* analysis suggests because competition and other factors lower it. An increasing number of studies are attempting to quantify the value of overcoming these barriers, although they are subject to a great deal of uncertainty. One such effort by the Regulatory Assistance Project (RAP) in Vermont provided a dramatic calculation of the benefits (see Table 7.6).

Table 7.6 cross-tabulates the RAP analysis with the results of a European study that also evaluates the value of efficiency. Moreover, when considering supply-side alternatives, the value placed on each of these effects is measured by the net difference between the two alternatives, which tends to be considerably smaller than the net effect of efficiency. Efficiency is very low-cost and tends to reduce direct resources costs because less electricity is consumed. How much value a resource (other than efficiency) has depends on its cost and the nature of the resource. It shows that there is a close correspondence between the benefits identified. In the RAP study the cost of energy efficiency is about \$40/MWh that compares favorably to the benefits it delivers. There are four broad categories of benefits from reduced consumption—generation savings, other system

Table 7.6 The Benefits of Efficiency as Externalities

OECD/IEA	RAP/ACEEE Value			
Economic	**Utility System**	**Participant**	**Societal Nonenergy**	**($/MWh)**
Provider Benefit	Generation,		Reduced Terminations	57.5
Infrastructure	Transmission, Capacity		Reduced Uncollectibles	3.2
	Distribution,			20.0
	Line Loss, Reserves			10.2
	Credit & Collections			
	Reserves			.7
	Risk			2.3
	Total Other Utility			36.4
Total Economic				
Energy Prices	Demand Response			
	Price Effect			
Public Budgets				
Energy Security	Reduced Risk		Societal Risk & Security	
Macroeconomic			Employment, Development	
			Productivity, Other Economic	
Environment				
GHG Emissions		Obligations & Costs	Obligations & Costs	40.0
		Avoided Regulatory	Avoided Regulatory	
Resource Mgmt.			Electricity/Water Nexus	
Air/Water			Air Quality	
Pollutants			Water Quantity & Quality	
			Coal Ash & Residuals	

Social		
Health	Health, Comfort, Noise	9.3
Affordability	O&M	17.4
	Other Resource Savings	25.2
Access	Low Income Consumer Needs	
Development	Quality and Durability	
Job Creation	Employment	
Asset Values	Property Values, Resale	
Disposable Income	Bill & Transaction Cost Savings	
Productivity	Productivity, Reduced Sick Days	
Total Social		51.9
Total Cost		185.8
Cost of Efficiency		40.0

Source: Jennifer Thorne Amann, *Valuation of Non-Energy Benefits to Determine Cost-Effectiveness of Whole-House Retrofit Programs: A Literature Review*, American Council for an Energy Efficient Economy, May 2006, 8; James Lazar and Ken Colburn, *Recognizing the Full Value of Energy Efficiency: What's Under the Feel-Good Frosting of the World's Most Valuable Layer Cake of Benefits* (Montpelier, VT: Regulatory Assistance Project, 2013), 6; Lisa Ryan and Nina Campbell, *Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements*, Insight Series (Paris, France: International Energy Agency, 2012), 25.

cost savings, environmental and social. It costs about 50 percent more to produce electricity than to save it. Each of the other categories of benefits is roughly equal to the cost of efficiency. On the whole, the benefits of efficiency are more than three times the cost and this does not take into account significant macroeconomic benefits that the study identifies in qualitative terms.

CLIMATE CHANGE LITERATURE

Table 7.5 identifies the recent empirical studies of climate change in the market imperfections and barriers framework. There are strong parallels between the empirical findings in the analysis of the response to climate change and the efficiency gap analysis. One significant difference between the two literatures is that the climate change literature contains a significant number of studies that directly evaluate the impact and efficacy of specific policy instruments. This reflects the fact that, as a policy challenge, climate change is more urgent, specific, and larger than the efficiency gap. In the appendix for the climate change studies, we identify each market imperfection addressed and offer a sample citation to describe it.

Externalities

There is a very large literature on the externalities associated with energy consumption. Importantly, it goes well beyond the negative national security and environmental externalities, which are frequently noted in energy policy analysis. These large negative externalities associated with the fossil fuel-based electricity sector are the proximate cause of the need to re-center the sector on alternative resources. The need for change is great and urgent. However, the negative externalities are not the only obstacles confronted by the transformation. Other market barriers and imperfections must be overcome to control the cost and speed of the transition to a new electricity system.

The central observation on the supply-side is that many of the benefits of alternative generation technology resources, or the processes by which their costs would be reduced (e.g., public good qualities of research and development, learning by doing, network effects), are positive externalities themselves. This means the private sector will underinvest. Long lead times for technology development, increasing returns to scale, and network effects make entry difficult.

The macroeconomic effects of energy consumption and energy savings are important externalities of the efficiency gap. Two macroeconomic effects have begun to receive a great deal of attention: multipliers and price effects. The ability to increase macroeconomic activity—or more importantly in the case of climate change, moderate reductions in macroeconomic activity that flow from shifting energy resources—is an important policy consideration. Choosing least-cost approaches to decarbonization is critically important from the macroeconomic perspective. Reducing energy consumption tends to reduce spending on economic activities that have relatively small multipliers (especially when energy imports are involved as in the transportation sector) and increase economic activities that have large multipliers (including the direct effects of spending on technology and the indirect effect of increased household disposable income).

Information

Information plays a very large role in the LBNL and RFF efficiency gap analysis. Information presents a problem at the societal level because it can be considered a public good that is not produced. This is because the authors of the information cannot capture its social value. Information is a structural problem because, where it is lacking, even capable, well-motivated individuals cannot make efficient choices. A transaction cost problem also arises when information is costly or difficult to verify. Where information is asymmetric, individuals can take advantage of the less informed to produce outcomes that are not efficient. It is also a problem at the behavioral level where individuals lack the ability to gather and process information.

Inertia on the Supply Side

New technologies face significant barriers to entry that are compounded by the existence of entrenched incumbents. The inertia that supports the incumbent technology is a central barrier. Inertia is the result of several market imperfections (including market structure) and endemic, behavioral, and transaction costs that exacerbate the problem of underinvestment in alternatives. Inertia enables dominant incumbents to implement practices and promote policies that magnify the barriers to entry, such as control of access to the grid or dispatch.

The long period of dominance of fossil fuels has created a large market, making it the focal point of resources, investment, and innovative activity. Since the alternative technologies are at a disadvantage in terms of development and the ability to attract resources, just raising the cost of the dominant fuels does not overcome the inertia. It actually allows the gap between the incumbent and alternative technologies to persist, or even grow, as the entrenched interests use their resource advantage and political power to protect their incumbency. Dislodging a dominant technology requires overcoming a great deal of physical and institutional inertia built up over decades.

Market Structure and Transaction Costs

Beyond inertia, market structural problems are equally important, including market size, the tendency to invest in incremental innovation focused on the dominant technology, innovative activity and existing skill sets, lack of substitutability between the alternatives, limited spillovers from innovation in the incumbent technology, and the undifferentiated nature of the product. These structural problems make it hard for new entrants to secure a foothold (niche) from which to build scale and learn by doing. Uncertainties about the nature of the market, the value and cost of technology, and limitations of technological expertise and information play an important role in increasing the cost and raising the risk of adopting new technologies.

As a result of these factors, the marketplace yields a limited set of choices because producers and consumers operate under a number of constraints. Split incentives flowing from the agency problem are a frequently-analyzed issue. When the purchaser of the energy-consuming durables and the users are different people, inefficient choices result.

Slow Responses on the Demand Side

Consumers and producers are poorly informed, influenced by social pressures and constrained in their ability to make the calculations necessary to arrive at objectively efficient decisions. Consumers and producers apply heuristics that reflect a rationality bounded by factors like risk and loss aversion. Inattention to energy efficiency is rational, given the magnitude, variability, and uncertainty of costs, as well as the multiattribute nature of energy-consuming durables. The product is a bundle of attributes in which other traits are important and energy costs are hidden costs. The resulting energy expenditures are important components of total household spending. Important benefits of energy-consuming durables may be “shrouded” in the broader, multiattribute product.

Consumers are influenced by social norms and advertising. Consumers respond sluggishly to price increases, so raising prices or shifting the risk of price volatility onto the consumer will not have the desired effect in stimulating demand for alternative resources. Energy-consuming durables have long lives, and consumers frequently do not make the purchase decision. Consumers and the agents who make the purchase decisions are first cost sensitive, and they have difficulty projecting energy prices and quantities to make lifecycle cost calculations. The demand-side does not receive attention commensurate with its importance as a source of market failure or its potential impact on the transition to a decarbonized sector.

8

THE NUCLEAR WAR AGAINST THE FUTURE

INTRODUCTION

At a turning point such as this, many discrete decisions take on larger significance as they combine to define a new direction for the political economy. The institutional transformation is not only between the past and the future, but also between alternative futures. Once decarbonization is embraced as the primary direction of change, the competition among low-carbon alternatives intensifies. The fossil fuel industry has chosen to defend antiquated technologies and resist decarbonization rather than develop technologies that enable their resources to be used in a carbon-constrained economy. As a result, in the contemporary environment, the competition is primarily between two low-carbon alternatives that are incompatible: renewable distributed resources and central station nuclear power.

Nuclear power advocates harp about being low-carbon to try to leverage a position in the low-carbon future resource mix, but that claim is nowhere near significant enough to win the day. The economics of nuclear power are so abysmal—and its environmental impact so much worse than the renewable/distributed/demand-focused alternatives—nuclear power barely merits a footnote in the analysis of the low-carbon future. However, because incumbent nuclear interests are powerful in the contemporary terrain of political economy (and many are state-run or subsidized entities), nuclear power commands more resources and requires more attention than it deserves. The primary thrust of this book is to make the case for the renewable options, but the analysis of nuclear power must be a subtheme—an unfortunate but necessary distraction.

A large part of the institutional recomposition to build the physical and institutional infrastructure that will support the emerging electricity system involves overcoming the inertia of incumbent interests and entrenched approaches. In the electricity sector, the battle for change runs into the central station interests who dominated the 20th-century structure. The war those interests fight against the future is a major front in the struggle for change, which is the topic of this chapter.

At this moment, nuclear power demands attention as a subtheme of the analysis because its advocates claim it must be a part of the solution. Indeed, some go so far as to call for a 100 percent nuclear future. Because these claims are made in spite of nuclear power's extremely high cost, continuously abysmal record of cost overruns and construction delays, serious environmental and public health impacts, and fundamental incompatibility with renewable resources, it merits a discussion—one that not only explains why nuclear power should not be included as an asset in the long-term, low-carbon portfolio, but also how nuclear interests are seeking to secure a place for nuclear power in the future by slowing and distorting the institutional structure that the transformation of the system requires.

Fossil fuel interests—above all, coal-based—have a broader agenda. They, too, need to preserve the institutional structure that favors central station generation. Their interest would best be served by denying the need to decarbonize altogether, or insisting that carbon capture technologies are necessary. They carry a heavier burden in the contemporary terrain of the political economy of energy. Here we focus on the nuclear interests since, with their claim to being low-carbon, their overall claim to a place in the portfolio of future electricity resources is more challenging.

THE ECONOMIC MOTIVATION FOR THE NUCLEAR ATTACK ON EMERGING ELECTRICITY SYSTEM

The 20th-century electricity industry relied on baseload facilities that ran constantly to meet off-peak demand. Rather than store electricity itself, which was costly, utilities chose to meet higher demand (shoulder and peak) by storing raw energy that could be used to quickly generate electricity (primarily fossil fuels like natural gas and diesel, but also a small amount of water pumped above a generator). For fossil-fuel peak power, operating costs were high but capital costs were low, so it made sense to run these facilities for a small number of peak hours. By allowing peak prices to skyrocket (known as hockey-stick price increases) and paying those prices to all generators, scarcity rents were created that could be used to pay the high capital cost of the baseload facilities.[1] Where prices were set by regulators, they were put far above marginal costs for the same reason.

Over the past two decades, it has become much costlier to meet demand the old way. First, diesel became expensive and volatile. Second, the social costs of fossil fuels have been recognized. Third, carbon emissions have become a major concern. The search for low-carbon alternatives to replace coal baseload generation has unleashed a wave of innovation. Innovation has led not only to a dramatic lowering of the cost of renewable alternatives, but also to the use of resources that are likely to be dispatched on-peak because they have very low operating costs and periodic high availability. As these resources come online, they shift the supply curve, putting downward pressure on the market clearing price and the scarcity rents available for capital recovery, while they shift the peak later in the day.

Thus, market developments compound the capital cost problem of new and old nuclear reactors. The wholesale price does not allow a margin for capital cost recovery, but that is not all. Aging reactors are afflicted with another problem: escalating operating costs. The high operating costs of aging reactors has combined with the high construction cost of new reactors to create a perfect economic storm that has sunk nuclear power as an option for the 21st-century decarbonized electricity sector.

Several financial institutions who cover electricity have projected that renewables will account for the overwhelming majority of new U.S. capacity in the next decade, with declining cost of renewables putting pressure on the revenue streams of conventional resources. Credit Suisse notes that their projected low estimate for solar less than three years ago was higher than the actual solar Power Purchase Agreement (PPA) prices.

> Renewables are cost competitive to even cheap against conventional generation. The clearing price for new wind and solar continues to fall with improvements in utilization and falling capital costs. For wind we are seeing utilization rates 15–20 percentage points higher than 2007 vintage turbines, regularly supporting PPA pricing at or below $30/MWH that effectively 'creates' long-term equivalent natural gas at <$3/MMBtu. Lower capital costs for solar have dropped PPA pricing to $65–80/MWH from well over $100/MWH, making solar competitive with new build gas peaking generation.[2]

In fact, contracts are being signed at prices substantially below that level. As shown in the top two graphs in Figure 8.1, operating costs for wind have been declining. This stands in direct contrast with the increasing operating costs of nuclear reactors. In the mid-1990s, nuclear reactors would have been dispatched before wind with a substantial operating cost advantage. Two decades later, wind has a substantial price advantage that is likely to grow in the years ahead. The upper graph in Figure 8.1 includes estimates for the cost of keeping aging reactors online. The operating costs are quite high, and total costs are higher still—well above recent market clearing prices.[3]

The flashpoint of the conflict over the transformation of the electricity sector is captured in the lower graph of Figure 8.1, which is taken from an analysis by a group advocating for nuclear power. It centers on the market clearing price of electricity in those areas where markets (as opposed to regulators) set that price. The addition of wind lowers the market clearing price, which is undermining the economics of aging nuclear reactors. In the "merit order effect"—documented in every nation where the use of wind

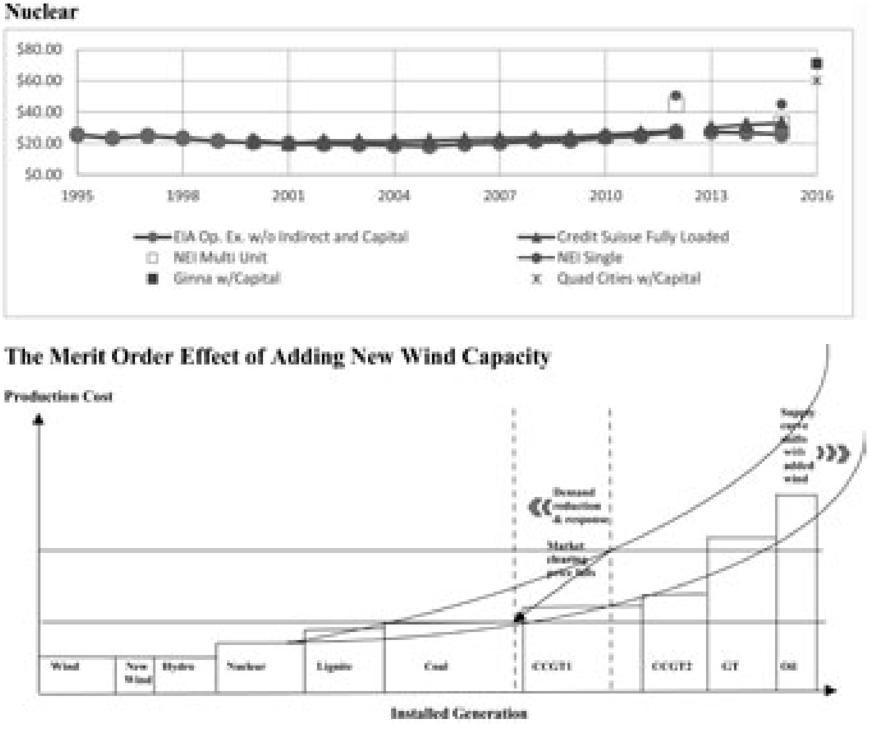


Figure 8.1 Average O&M Costs ($/MWh)

Sources: U.S. Energy Information Administration, *Electricity Annual*, 2015, Table 8.4; NEI *Nuclear Costs in Context*, April 2016; Nuclear Street News Team, "NEI Lays Out the State of Nuclear Power," Nuclearstreet.com, February 26, 2014; Credit Suisse, *Nuclear… The Middle Age Dilemma? Facing Declining Performance, Higher Costs, Inevitable Mortality*, February 19, 2013, p. 9; Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection Agency, Illinois Department Commerce and Economic Opportunity, 2015, *Response to the Illinois General Assembly Concerning House Resolution 1146*, January 5, Real price increase to break even, plus $11/MWh for capital.

has increased significantly[4]—wind backs inefficient natural gas (and some coal) plants out of the supply needed to clear the market at the peak. This lowers the market clearing price, which results in substantial consumer savings. Figure 8.1 shows that reduced demand compounds the problem.

The downward pressure on market clearing prices has led to a several years of losses for the aging nuclear reactors. Operating costs alone are almost twice the current market clearing price of electricity and, as the discussion below shows, things are likely to get worse over time. These reactors cost more to run than the alternatives, so they cannot cover their operating costs or make any contribution to ongoing capital costs that are necessary to keep them online. In the near term, numerous aging reactors are predicted to lose millions of dollars per year, although the amount of the losses will vary from market to market.

Thus, coal, natural gas, and subsidies are not the ones giving aging nuclear reactors heartburn, but rather it is the superior economics of wind and efficiency combined with the increasing operating costs of aging nuclear reactors themselves. It is important to recall that both the Lazard and Jacobson cost projections were estimated as subsidy-free costs. The "merit order" predicament in which nuclear power finds itself is deeply ironic. Historically, nuclear power presented itself as a low-cost option by emphasizing its low operating costs, downplaying its very initial high fixed capital costs, and glossing over ongoing capital costs to keep them online. Two decades of technological innovation in renewables, and the aging of extremely complex nuclear facilities, has put an end to that sleight of hand.

Utilities in New York,[5] Illinois,[6] and Ohio[7] asked for above-market prices for six reactors. These reactors have lost hundreds of millions of dollars over the last couple of years, but the utilities claim that the low price of gas is the cause of the problem. This is incorrect in three respects. First, the rising cost of operating reactors accounts for about a third of the problem. Second, the addition of wind, which backs inefficient gas out of the market clearing price, contributes to the shift. And third, demand has declined due to increased efficiency. The price of gas matters as well, but less than the other three factors. Two-thirds of the revenue shortfall experienced by aging reactors is caused by the rising cost of keeping nuclear reactors online, the superior economics of renewables, and the attractiveness of efficiency.

Against this background, the Rocky Mountain Institute's (RMI) *The Economics of Load Defection* is instructive. The analysis concludes that solar with battery storage will trigger a large wave of "grid defection" in five to ten years.[8] It shows that refusing to offer payment that reflects their value to the consumers who install this equipment could delay the impact by about a decade, but it will arrive in any event. RMI's message, aimed at utilities, is that their interests would be better served if they use the transition to build a system that accommodates and manages the transition, rather than being overwhelmed when it comes.

However, one could take the opposite lesson from this analysis. If this one policy (impeding net energy metering) can delay the transition significantly for a decade, utilities might see this as an opportunity to protect their short-term interests and secure an alternative long-term structure. By layering a number of attacks on the alternatives while simultaneously securing policies that advance their economic interests, utilities can significantly delay and alter the shape of the future. This interpretation is more consistent with their behavior and it suggests that the current battle over fundamental policies—subsidies, rate structures, deployment of physical facilities, and so on—are strategic, and could profoundly affect the future structure of the industry.

RMI recognizes that if the path of greatest resistance is taken by the utility industry, there will be a significant cost whatever the ultimate outcome, and the key decision point is at hand.

> These two pathways are not set in stone, and there is some room to navigate within their boundaries. But decisions made today will set us on a trajectory from which it will be more difficult to course correct in the future. The time frame for making such decisions with long-lasting implications for the future grid is relatively short, and is shorter and more urgent for some geographies than others.[9]

RMI is certainly not the only one to suggest that there is a direct link between policy choices and industry structure. The baseload-dominated electricity system was created by policy support and subsidies for physical and institutional infrastructure that favored a specific type of technology. The dominant incumbents will seek to slow or stop the spread of alternatives by denying their access to a similar process that they understand well.

> Their diffusion can be slowed by effects of path dependence and lock-in of earlier technology systems. . . . High carbon technologies and supporting institutional rule systems have co-evolved, leading to the current state of "carbon lock-in." For example, reductions in cost and the spread of infrastructure supporting coal- and gas-fired electricity generation enabled the diffusion of electricity-using devices and the creation of institutions, such as cost-plus regulation, which encouraged further investment in high carbon generation and networks. This created systemic barriers to investment in low carbon energy technologies. . . .

> The proposition that industries or technologies whose ascendancy is threatened by new competition tend to respond, carries some weight. It also suggests that actors, such as large energy companies, with substantial investments in the current system and its technologies, and relatively strong political influence, are likely to act to frustrate the implementation of institutional changes that would support the implementation of low carbon technologies.[10]

The economic conflict of interest between nuclear power and the lower-cost, low-carbon alternatives is reinforced by fundamental differences between central station power and distributed resources, both in terms of technological competence and institutional requirements. Lovins elaborated earlier on these deep-seated sources of conflict, making it clear that a truce that tries to accommodate both sides is neither very likely, nor good policy.

> "All of the above" scenarios are . . . undesirable for several reasons. . . . First, central thermal plants are too inflexible to play well with variable renewables, and their market prices and profits drop as renewables gain market share. Second, if resources can compete fairly at all scales, some and perhaps much, of the transmission built for a centralized vision of the future grid could quickly become superfluous. Third, big, slow, lumpy costly investments can erode utilities' and other providers' financial stability, while small, fast granular investments can enhance it. Competition between those two kinds of investments can turn people trying to recover the former investments into foes of the latter—and threaten big-plant owners' financial stability. Fourth, renewable, and especially distributed renewable, futures require very different regulatory structures and business models. Finally, supply costs aren't independent of the scale of deployment, so PV systems installed in Germany in 2010 cost about 56–67 percent less than comparable U.S. systems, despite access to the same modules and other technologies at the same global prices.[11]

In short, this clash is inevitable and has given rise to a frontal assault by nuclear advocates on alternative resources and the institutions that support them (see Table 8.1).[12]

CREATIVE DESTRUCTION AND CONSTRUCTION

Our analysis argues that the electricity sector is on the cusp of a major transformation, which will have powerful implications for the structure

Table 8.1 The Nuclear Industry's Broad Attack on Renewables

	Federal	States
Direct (Attack Programs that Support Renewables)		
Renewable Energy Production Credit[1]	X	X
Renewable Energy Portfolio Standard[2]	X	X
Efficiency Portfolio Standard[3]	X	X
Net Metering		X
Taxes and Fees[4]	X	X
Indirect (Implement Programs to Support Nuclear)		
EPA Rule Bias[5]	X	X
Wholesale Market Manipulation		
Above Market/Guaranteed Rates	X	X
Alter Dispatch Order to Favor Base Load[6]	X	X
Restrict Demand Response[7]	X	X

Notes:
1) General opposition to and specific cutbacks in renewable commitments.
2) Includes shifting from "renewable" to "clean" standard.
3) General opposition to and specific cutbacks in utility efficiency programs.
4) Taxes on renewables, Minimum Offer Price Rules.
5) Allowing subsidies and incentives for nuclear. Giving system benefits for reliability, onsite fuel storage.
6) Must run rules/Take or pay clauses.
7) Opposition to bidding demand response in wholesale markets.

Source: Nuclear Information and Resource Service, *Killing the Competition: The Nuclear Industry Agenda to Block Climate Action, Stop Renewable Energy, and Subsidize Old Reactors*, NIRS Report, September 2014.

of the sector. It is part of the rapid and continuous process of creative construction, overlaid on the underlying creative destruction brought about by the technological revolution in energy and communications technologies.[13]

The magnitude of the destruction will be huge, with many trillions of dollars of sunk investment devalued and replaced by low-carbon, lower-cost electricity generation technologies and more energy-efficient durable goods.[14] As discussed in Chapter 6, if the least-cost route to a low-carbon economy is taken, the investment needed for the new technologies will represent a shift in spending, not a large increase. The investment in new technology replaces the old, and a new technology paradigm destroys the old one (although it can unfold over decades). The dominant incumbents will vigorously defend their interests.

The industry recognized the threat as early as 2012 and launched a private campaign to respond. At a Board and Chief Executives meeting of the Edison Electric Institute (EEI), the utility industry's trade association outlined an "action plan" called *Facing the Challenges of a Distribution System in Transition*, which concluded that:

> Transition creates new challenges for utilities:
>
> - Prospect of declining retail sales,
> - Financing of major investment in the T&D system; workforce issues,
> - Potential obsolescence of existing business and regulatory models.[15]

For the chief executives, the challenge was: "How do you grow earnings in this environment?" The culprits were "loss of customers" and "competition." The target of the campaign was identified as "hidden subsidies like net metering [that] allow higher income customers to avoid system costs (pay little distribution or other fixed costs, despite the fact that they impose new costs on the system), which are then paid by middle class and lower income customers." The strategy was to "raise concerns about net metering" among customers, policy makers, and regulators—a strategy that was vigorously implemented. The ultimate goal was to secure the utilities' central role in the future utility system:

- Gain support for utility involvement in DG [distributed generation] and microgrid space;
- Promote fleet and off-road transportation applications;
- Incorporate multisite DC [DataCenters] companies into National Key Accounts Program;
- Provide members with DC market activities, best practices, and competitive intelligence;
- Site utility-owned generation on DoD [Department of Defense] land; and
- Expand Utility Energy Services Contracts and privatization initiatives.

Independent financial analysts began signaling the dramatic impact that the emergence of the 21st-century electricity market could have on the 20th-century utility business model.[16] The direction of change, however, will merely bring the electric utility sector into line with the changes that have been sweeping across other sectors of the economy.

> The electric utility business model has remained stubbornly unchanged for much of the last 50 years. While telecoms, health care,

> and other industry structures have hurtled ahead—for better or worse—in response to our modern technological and regulatory framework, the system that powers our homes and businesses seems almost anachronistic at this point.[17]

It is not only high-capital cost generation that is feeling the profit pressures. "Disruptive" has become the watchword for utility analyses.

> These changes (or "disruptive challenges") arise due to a convergence of factors, including: falling costs of distributed generation and other distributed energy resources (DER); an enhanced focus on development of new DER technologies; increasing customer, regulatory, and political interest in demand side management technologies (DSM); government programs to incentivize selected technologies; the declining price of natural gas; slowing economic growth trends; and rising electricity prices in certain areas of the country. . . . The industry and its stakeholders must proactively assess the impacts and alternatives available to address disruptive challenges in a timely manner.[18]

EEI's action plan recognized the potential disruption, as well. A year later, EEI formed an alliance with a leading environmental group, the Natural Resources Defense Council (NRDC), to call for changes in tariff and rate structures that recognize the emerging reality.[19] Their joint statement recognizes the inability and inappropriateness of recovering capital costs in variable charges, and the need to transform the grid and its operation into a two-way network that supports decentralized behaviors at the edge of the network to improve the efficiency of the sector. It also recognizes that this will require a physical and institutional transformation.

Nuclear utilities have not only supported the broad industry defense of the utility business model by trying to undermine the alternatives, they also have sought to increase the income of the central station facilities. Since marketplace evidence clearly indicated that new reactors have long been uneconomic and aging reactors had become uneconomic, nuclear advocates made a plea for above-market prices to divert attention from both the short-term (merit order) and long-term (levelized cost) measures of resource cost. They claimed some "hidden" value for services provided by central station power—above all, reliability—while rejecting alternative approaches to getting those services.

The central approach was to claim that baseload generation is needed to maintain the reliability of service, and that the market was not recognizing this value. This argument was also expressed in a way that extends the support to coal-fired generation, where reliability is deemed to take precedence over decarbonization. Nuclear advocates combine the reliability claim with the need to reduce carbon emissions to conclude that nuclear is indispensable to the effort to respond to climate change.

The arguments did not have nearly the effect that nuclear advocates hoped. After four reactors had been retired in a very short time—one for economic reasons and three for maintenance problems—the industry escalated the attack with threats to retire more aging reactors early. The industry intended to create a sense of immediate and urgent crisis, which gives it leverage over policymakers. In the mid- and long terms, the reliability issue involves the ability of the grid to be managed with much higher levels of renewable energy. The previous chapter looked at emerging approaches to delivering long-term reliability in a 100 percent renewable/distributed/demand-based approach. Here we will examine the short and mid-terms, which lead to a similar conclusion: the reliability crisis/challenge proves to be more fiction than fact.

We will examine three cases:

- Exelon's threat to close a number of nuclear reactors and its pursuit of subsidies triggered an intensive analytic exercise in Illinois, which gives insight into the short-term issues;
- First Energy in Ohio as a variation on the Exelon theme; and
- PG&E's application for a license renewal for Diablo Canyon ten years before the expiration of the current license, providing an ideal opportunity to look at the mid-term issues.

THE FALSE RELIABILITY CRISIS: EXELON'S NUCLEAR RETIREMENT BLACKMAIL

Exelon is the largest nuclear utility in the United States (with a total of 14 reactors), and Illinois (with 6 reactors), where it is headquartered, has more nuclear reactors than any other state. The two regional transmission organizations (RTOs) into which Exelon sells power—MISO and PJM—have the largest number of nuclear reactors by far. Exelon claimed that it would have to close many of its reactors if it did not get financial relief. This was part of an aggressive campaign to get more favorable treatment for its reactors from state, regional, and federal policymakers, with Illinois being the focal point.

State policymakers resisted, deflecting the initial demand for new laws to favor nuclear. They called for state agencies to study the impact of the early retirement of aging nuclear reactors, and the outcome was exactly the opposite of what Exelon had hoped for. The State of Illinois agencies' analyses concluded that there would be no crisis that merits rate increases of billions of dollars over the next decade.

First, from both the reliability and carbon-reduction points of view, the amount of at-risk nuclear power is not large enough to warrant immediate subsidization without an evaluation of the cost of the available alternatives. Since the alternatives are clearly lower in cost, the advocates of nuclear power focus on reliability and other systems. Since the level of renewable resources in the United States is well below the level at which concern might arise, there is little threat to reliability in expanding variable renewables. There are a host of approaches to managing the grid that can ensure reliability even as the share of variable renewable resources rises substantially.[20] Therefore, it takes a set of worst-case assumptions devoid of foresight, planning, and preparation to yield a hint of concern about reliability in the near term.

> Resources in both RTOs are adequate in the "base case," and continue to be adequate when the at-risk nuclear plants are retired in the "nuclear retirement case." In MISO resources remain adequate if the nuclear plants are retired even if there is a "polar vortex" event, but not in the "high load and coal retirement" case. On the other hand, resource adequacy is substandard in PJM in both stress cases; but demand response mitigates the problem in the "high load and coal retirement" case. . . . The IPA attributes the superior resource adequacy in Illinois, even given the premature closures of the nuclear plants, to its initial capacity surplus and to its robust transmission system that enables Illinois to call on out of state capacity support.[21]

RTOs have rules that require notice about decisions to abandon generation, which affords the operator and market participants time to adjust, and also imposes penalties for failing to deliver on existing commitments.[22]

> Usually, nuclear plant closures are not sudden unheralded events. Rather they are planned and anticipated months or even years in advance. This would be particularly true of a closure prompted by low power prices rather than a serious accident or the unexpected failure of plant equipment.[23]

To the extent that the early retirement of several reactors might put pressure on the electricity system, the Illinois analysis found that responses are available, and that it would not be an Illinois-specific problem but a regional problem. In some senses, such an event immediately triggers mitigating responses.

> Thus, the eventual closure of a generating facility could be accompanied by a variety of actions by the affected RTO to alleviate reliability concerns.[24]

To the extent that a problem might be caused by the closure of multiple reactors, it would elicit responses from other market participants to mitigate the impact.

> Such actions would also have the effect of increasing the supply or availability of other generating resources or the supply of demand response resources. Such actions would moderate what might otherwise have been a sudden increase in energy market prices.[25]

At the same time, the analysis notes that the transmission system has built-in mechanisms that respond to the challenge. The list of immediate potential short-term responses is quite long, including obligations of the utility to assist in preserving system reliability, redispatch and reconfiguration of resources, management of planned outages, and expansion of transmission facilities.[26]

Economic Cost

The Illinois analysis went beyond the focus on reliability to consider the impact of a reactor closure on the economics of the system. Not only did it conclude that response mechanisms would be driven by basic economics, but it noted that the overall impact could be positive if more economic resources are brought online.[27]

In the case of Exelon Illinois, the threat to abandon a large amount of capacity represents an exercise of market power,[28] which would raise prices for the facilities that remain online. In fact, there is presently a surplus[29] that Exelon may be trying to drive out of the market. The finding that closing uneconomic aging reactors in Illinois has little impact highlights that the proper level of analysis is multistate, and that reliability is not the primary concern.[30] Spreading the impact across a wide area and a significant period (which gives the system time to react) results in almost no cost or reliability damage. Simply put, nuclear reactor retirement can be a nonevent.

The Illinois Department of Commerce expresses the belief that, "Eventually, market forces and national policies will fully compensate nuclear plant operators for their reliability and carbon-free emissions."[31] We have shown that the market fundamentals are pressing in the opposite direction. Indeed, the more public policy relies on "effective market-based solutions" to solve the problem of reducing carbon emissions, the less likely that nuclear reactors will be supported. In the long-term supply stack of low-carbon resources, nuclear is the costliest resource.

The Illinois analysis provides support for the merit order problem confronting nuclear power at a granular level, as shown in Figure 8.2. Several of the aging reactors in the Exelon Illinois fleet showed losses in 2009 after running significant surpluses in 2007 and 2008. As natural gas prices rose in 2010, they broke even. However, in 2013, when the price of natural gas was very similar to the price in 2010, the reactors were again losing money.

The Illinois analysis provides important insight into this issue by citing an EPA analysis of PJM, into which the majority of the at-risk reactors in Illinois sell. As the ICC notes, "the EPA conducted its own analysis of the costs of compliance with its proposed CO_2 regulations." For the purpose of

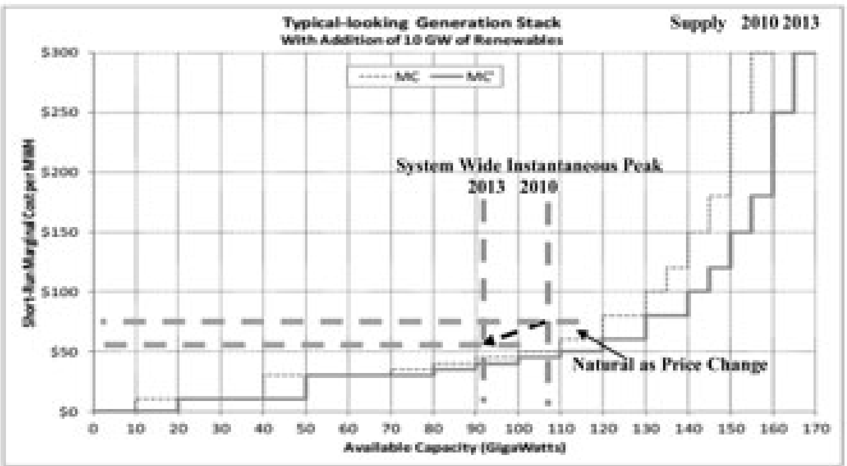


Figure 8.2 Impact of Merit Order and Declining Demand Based on MISO Changes[32]

Sources: Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection Agency, Illinois Department of Commerce and Economic Opportunity, *Potential Nuclear Power Plant Closings in Illinois: Impacts and Market-Based Solutions, Response to the Illinois General Assembly Concerning House Resolution 1146*, January 5, 2015, for the supply stack. MISO demand shift is from MISO, *Annual Market Assessment Report: Information Delivery and Market Analysis*, June 2014, 14, 16, 20.

examining the early retirement of nuclear reactors, the implication drawn by the ICC is that more resources are in the offing for reactors, diminishing the need for Illinois to take state-specific action.[33] All of the alternative low-carbon scenarios in EPA's analysis have lower wholesale costs than the business-as-usual base case, echoing the earlier findings on cost. Keeping in mind that the EPA did not project any increase in nuclear reactor output, emissions reductions are achieved by replacing coal using the following (listed in accordance with the magnitude of the contribution): demand reduction, natural gas, improved coal efficiency, and non-hydro renewables. The overall reduction in the wholesale price of electricity nationwide is at least one-third—and could be as high as one-half—if the most efficient, regional approach to compliance is taken. The ICC analysis ends with a more precautionary note, emphasizing the importance of taking a regional view[34] and recognizing the importance of a "holistic" approach.[35]

The opportunity to reduce carbon emissions by adding resources with costs below the current average has long been recognized. In fact, the former head of Exelon, John Rowe, frequently made this argument using the carbon supply curves for Exelon and PJM.[36] The efforts of Exelon to impair the alternatives and extract subsidies may reflect the continuing deterioration of nuclear economics. In the five years after Rowe began making the argument that there was a low-cost approach available, the cost of wind and solar (as measured by purchased power agreements) had declined dramatically, as had the price of natural gas. The cost of nuclear construction and aging reactor operation, on the other hand, increased substantially.

FIRST ENERGY

In the introduction to this chapter, we explained why focusing on nuclear power rather than coal provides a better perspective on the conflict between traditional generation and renewable resources. Because advocates can claim that nuclear energy is low-carbon, the attack that they have launched on the alternatives distills the clash of economic interests and institutional conflict between central station power and renewable resources. However, the underlying structural problem that afflicts nuclear power also affects coal. Some utilities have both coal and nuclear resources. The effort of one mixed utility, First Energy, to obtain subsidies from Ohio ratepayers reaffirms earlier observations on Exelon's quest for subsidies in Illinois, adding additional perspective to the ongoing conflict.

In terms of purchase power agreements, First Energy provides predominantly coal (58 percent), and a substantial amount of nuclear (23 percent). Nuclear is its second resource by a wide margin, with hydro

(8 percent), oil and gas (9 percent), and wind and solar (3 percent) rounding out the list. In Ohio, where it was seeking ratepayer subsidies, it had roughly the same 2.5-to-1 ratio of coal to nuclear.[37] The unique thing about First Energy is that, over the last decade-and-a-half, it acquired coal assets and shed renewable assets when the industry was moving in the opposite direction. This "has not been a winning strategy"[38] because the same factors that have rendered aging nuclear reactors uneconomic have also made aging coal generators uneconomic.

> With an aging coal fleet, low natural gas prices driving down power prices, weak electric demand growth, and increasing penetration of energy efficiency and renewable energy . . . FirstEnergy's merchant power plants, which depend on being able to sell their output for more than their cost of operation, have been hit particularly hard. Indeed, a leading utility analyst has recently estimated that FirstEnergy Solutions, one of FirstEnergy's merchant generation companies, is worth less than $0.[39]

Each of the strategies Exelon pursued to bail out its nuclear plants has been magnified by First Energy in its own efforts to bail out its coal and nuclear facilities. First Energy has taken the war against the future further to the state and regional levels by actively reducing the level of resources available.

- It led the effort to reduce the commitment to renewables and efficiency in Ohio, and is actively seeking to implement that reduction on its system.
- It withheld demand resources from the regional power pool by refusing to bid them into the market. This doubled the market clearing price and raised the cost to consumers by hundreds of millions of dollars.
- It is pressing PJM to not allow demand response to be bid into that market, even though demand response is widely recognized as having a key role in ensuring reliability and mitigating price increases if markets become tight.

Placing First Energy's strategy over the past couple decades into the context of the electricity sector further reveals its extreme posture. First Energy also:

- Sought massive subsidies for its nuclear assets in the transition to a wholesale market;

- Shifted coal generation from the wholesale market to regulated status when it did not like the market price; and
- Has requested a direct subsidy from ratepayers.

In essence, First Energy is seeking to create a crisis of reliability by driving resources out of the market so that more baseload resources are needed. Its ability to lure policymakers down this path reflects more than the political muscle of a major utility, which is considerable. Over the past decade, the economics of the electricity sector has been transformed by technological change. Policymakers still have a mindset that is stuck in the past. The economics of aging reactors has been undermined by a 40 percent increase in the operating cost of those reactors; a 40 percent decrease in the cost of wind; a 60 percent decrease in the cost of solar; low-cost energy efficiency technologies that have taken a bite out of load growth; demand response that has become an increasingly valuable and effective resource; huge investments in storage technologies that are on the brink of redefining the value of intermittent resources; and advanced information and control technologies that transform the approach to reliability.

The strategy pursued by First Energy makes it clear that this is a fight to the finish between the central-station approach and the renewable approach. It provides strong support for Lovins' conclusion (cited earlier) that an "all of the above" approach simply will not work. It renders null and void the aspiration expressed by the Illinois Department of Commerce and Economic Opportunity that "Illinois has the opportunity to craft effective market-based solutions that can support all forms of low-carbon power generation to be sited in Illinois for the benefit of Illinois' economy and citizens."[40] Above all, it precludes any real possibility of significantly reducing carbon emissions and responding to the challenge of climate change.

The extremes to which the central-station generation advocates are willing to go to defend their interests in their war against the future suggests that retiring aging reactors and coal plants in an orderly fashion is an indispensable, early step on the path to building a least-cost, low-carbon future for the electricity sector.

BASELOAD BIAS, UTILITY SCALE FETISH, AND SHORT-RUN MYOPIA IN NUCLEAR LICENSE RENEWAL: PG&E'S DIABLO CANYON

Nuclear Regulatory Commission Guidelines

The PG&E application for a license renewal for its Diablo Canyon reactors represents a different point in the reliability debate—a mid-term, general claim about reliability. It also reminds us that institutional inertia in the public/regulatory sector is a critical factor in the transition between modes of production. Indeed, as noted, social institutions (government being the most prominent) are slower to change than economic forces and institutions.

The Nuclear Regulatory Commission's (NRC) Generic Environmental Impact Statement for License Renewal[41] gives guidance to utilities on the general criteria the NRC will apply in license renewal. In its updated GEIS in 2013, the NRC recognized that the energy field is evolving very rapidly, and therefore requires a case-by-case analysis of energy alternatives in license renewal proceedings, using "state-of-the-science" information.[42] However, a close look at the GEIS in the context of the contemporary industry shows quite clearly that two decades of rapid and dramatic economic and technological change have rendered obsolete even the modified standard that the NRC uses to evaluate requests for license renewal.

Under the 1996 Guidelines, the NRC framework for evaluating license renewal requests focused on nuclear reactors as baseload generation facilities.[43] The first page of the section on "Alternatives to License Renewal" concluded by stating that "therefore, NRC has determined that a reasonable set of alternatives should be limited to analysis of single, discrete electric generation sources and only electric generation sources that are technically feasible and commercially viable."[44] In the evaluation of the sources, the NRC invoked the concept of baseload over 30 times. The majority were references to the failure of renewables to meet the baseload criteria.

In the 2013 revision, that standard was revised somewhat. Utility scale replaces baseload as the central concept, while a reliable quantity of replacement capacity equal to the baseload capacity is the target. "The amount of replacement power generated must equal the baseload capacity previously supplied by the nuclear plant and reliably operate at or near the nuclear plant's demonstrated capacity factor."[45] The change is cosmetic, at best.

The NRC continues to exhibit an extremely narrow focus on utility-scale and baseload. In the current technological and economic environment, this focus is tantamount to an irrational baseload bias and a utility-scale fetish that is out of touch with reality. Section 2 of the revised relicensing regulation invokes baseload and utility-scale 25 times in the 16 pages where alternatives are evaluated. The assessment of the alternatives is defined by these two antiquated concepts. Moreover, the identification of alternatives does not include building new generation facilities, efficiency, or integrated management of supply and demand.

Ironically, the NRC suggests that the fact that PG&E is asking for the license renewal ten years in advance is a matter of necessity and routine.[46] This suggests that it takes as long to implement the steps necessary to extend the life of a nuclear reactor as it does to build a new one. Thus, aging reactors suffer from the same drawback that was demonstrated for new reactors in the earlier discussion. They are a very bad investment in a dynamic environment. An erroneous decision to approve the license extension under these circumstances imposes direct and immediate harm on consumers. It reinforces the utility's incentive and ability to resist the superior economic options that have become available, frustrating the transformation of the utility sector.

The PG&E Diablo Canyon Application

The harm of failing to give proper guidance to utilities can be seen clearly in the PG&E application for a license renewal for Diablo Canyon. PG&E continued to apply the standard from the 1996 GEIS. PG&E repeatedly cited the old standard to "disqualify" alternatives.[47] PG&E's focus on "standalone" energy sources reflects two unsupported biases—one toward reliance on "baseload" generation by a single source, and another toward "utility-scale" generation.

To appreciate why these developments deserve much more consideration than PG&E gave them, one need only compare PG&E's Amended Environmental Report with the California Energy Commission's documents. PG&E rejects the option of geothermal energy based on the assumption that a single new geothermal plant would have to be built in PG&E's service territory.[48] Conservatively assuming that the PG&E service territory includes half the geothermal resources in the state, geothermal resources are twice as large as Diablo Canyon capacity. Efficiency, renewables, and distributed generation potential are also about twice the size of Diablo Canyon.[49]

Adding in efficiency and other renewable resources, the alternative energy capacity would be four times the capacity of Diablo Canyon. Three-quarters of this capacity (geothermal and efficiency) is not variable, meaning that the 24-hour energy supply provided by Diablo Canyon could be replaced three times. Adding in renewables with storage would increase 24-hour availability of capacity to 3.5 times the capacity of Diablo Canyon. As discussed above, the ability of a well-managed 21st-century electricity grid that actively integrates supply and demand to deliver reliable power (while relying on renewable generation at much higher levels of penetration than would be necessary should Diablo Canyon retire) has been clearly illustrated.

Because PG&E is so focused on disqualifying alternatives based on the erroneous standard of "sufficient, single resource baseload power," it fails to conduct a responsible analysis of its own data. For example, in updating the Environmental Report from 2010 to 2015, PG&E provides data to show that a dramatic transformation of the sector is well under way. This trend includes reduced energy demand, greater capacity for managing demand, and greater reserve margins than existed even ten years ago.[50] The dramatic decrease in demand and sharp increase in reserve margins between 2008 and 2014 suggests that there is a lot more leeway to retire large, costly, inflexible reactors like those at Diablo Canyon. As shown in Table 8.2, the reduction in projected peak demand in a mere six years equals almost twice the total output of Diablo Canyon.

PG&E's analysis of the supply-side of the California electricity sector also obscures a simple fact: nonhydro renewables (i.e., wind and solar) have increased dramatically and are poised to surpass nuclear generation (which has been in decline) in the state. PG&E's analysis is also fundamentally weakened because it fails to recognize the dramatic development in battery technology that has been occurring over the past several years. Instead, PG&E focuses on pumped storage and compressed air. PG&E's failure to address battery technology is particularly egregious in light of the fact that many analysts conclude that batteries will play a key role in the transformation of the electricity system.

Declining costs of batteries are a key driver, as discussed, but so too is the increasing array of new technologies and applications, not to mention the additional critical and valuable functions they provide with increasing renewable penetration. Lazard and others see batteries as becoming the lowest-cost peak resource, which will team with renewables. For these reasons, batteries have already surpassed compressed air and are rapidly expanding as a storage medium.

Finally, PG&E makes the argument that Diablo Canyon is needed to reduce carbon emissions.[51] But PG&E relies on the results of a dated, 2009 EPRI analysis and makes no effort to consider its relevance to the current market situation. When change takes place as rapidly as it has in the

Table 8.2 Declining Demand Reduces the Need for Diablo Canyon Capacity

Level of Demand (GWh)	2008 View	2014 View	Change
Contemporary	**277.5**	**266.8**	**−10.7**
Projected	**314.0**	**280.0**	**−34**

Source: Pacific Gas & Electric (PG&E). *Diablo Canyon Environmental Report*, PG&E, 2015, 7.2-1.

present electricity sector, half a decade is a long time. In 2009, EPRI may well have still been under the spell of the "nuclear renaissance." The challenge of building 45 nuclear reactors in less than three decades in a nation that has not brought one online in the past two decades suggests the utter impossibility of this scenario. More importantly, that scenario is not the only approach to reaching climate change goals. Since 2008, the wind and solar capacity brought online in the United States has increased its total sevenfold. Much larger contributions from these resources are possible. The recent analysis from the Department of Energy suggested that wind alone could grow sufficiently to cover three-quarters of the proposed amount of nuclear. A simple projection of recent wind deployments would not only cover the shortfall, but retire a substantial part of the aging nuclear fleet.

CONCLUSION

To match the economic cost of renewables, nuclear power would need a technological revolution that has eluded it in its half-century of commercial deployment. Such an improbable revolution is very unlikely to take place in the time frame deemed critical to the fight against climate change. Nuclear power is equally unlikely to overcome its other severe environmental problems noted in Chapter 7.

Once the direction of a least-cost route to a decarbonized economy is set by the superiority of renewables, it becomes impossible for nuclear power to participate in the ultimate portfolio. The idea of pursuing an "all-of-the-above" scenario runs afoul of the fundamental differences between the 20th-century baseload fossil fuel approach and 21st-century renewable energy approach. The two technologies simply do not mix well because nuclear is not flexible. The vigorous attack on renewables launched by advocates of nuclear power in an effort to secure favorable treatment of aging reactors is testimony to the incompatibility between the two.[52] Gas has also fought renewables over market share. Much the same can be said of fossil fuels with carbon capture.

This analysis leads to three interrelated recommendations for policymakers.

- Policy should move to quickly adopt the necessary institutional and physical infrastructure changes needed to transform the electricity system into the 21st-century approach.
- Policy should not subsidize nuclear reactors, old or new. In the long term, their large size and inflexible operation makes them a burden, not a benefit in the 21st-century system.

- Nuclear's technological characteristics combined with the industry's political efforts to undermine the development of the 21st-century system makes nuclear a part of the problem, not the solution.

The outcome of this round of the battle for the future was mixed. Pressured by utilities to keep low carbon aging reactors online and with an eye toward looking at carbon reduction mandates, policy makers pursued a short-term all-of-the-above strategy, "recognizing" the value (reliability or low carbon) value of nuclear power, while maintaining or expanding a commitment to renewables.[53] With no new reactors moving forward in the areas that were the locus for the bailout battles, they put off the ultimate decision of what path to follow, but without impeding the 21st century alternatives, the economics we have discussed strongly disadvantaged nuclear.

Part V

POLICY RESPONSES AND DECISION MAKING TOOLS

9

THE URGENT NEED FOR POLICY ACTION: "COMMAND BUT NOT CONTROL"

INTRODUCTION

In this part we explain the need for and design of effective policies to overcome the challenges at two levels. Chapter 9 begins with a broad, macro view of the welfare economics of progressive policies. We then examine three of the most prominent proposed policy responses, price, direct subsidies, and performance standards. Finally, we articulate meso-level principles to guide the selection of progressive policy instruments and their implementation.

THE INTERSECTION OF MARKET FAILURE AND MASSIVE EXTERNALITIES

The efficiency gap analysis and debate discussed in Part IV has never been about externalities. Although the environmental, national security, and macroeconomic impacts of energy consumption stimulated interest in the value of reducing consumption, particularly after the oil price shocks and subsequent economic recessions of the 1970s, attracted attention, they are not the underlying cause of the efficiency gap. Because they are externalities, they are not priced into the market transactions and we would not expect market behavior to reflect their value. The efficiency gap arises from the failure of market transactions to reflect the direct resource costs of energy that are, or should be, reflected in its price and should influence behavior. It is a failure that is "internal" to the market.

Although climate change is an externality, we have not relied on external costs to drive policy, except in the broad sense of the preclusion of specific resources that results from the decision to decarbonize. To the extent that external impacts are associated with specific resources, we evaluated them qualitatively as additional factors that would be added to the analysis of economic resource costs. Since the low-carbon/low-pollution approach essentially pays for itself, we need not impute benefits to make the case for moving away from fossil fuels and nuclear. The large size of the external benefits calculated by Jacobson (close to $5,000 per person per year), argues for their inclusion in the analysis. Here we include the external benefits, but in a qualitative, rather than a quantitative manner.

Both climate change pollutants and other pollutants are important externalities. Quantitatively, however, the emission of other pollution is a larger problem. The Jacobson analysis finds that the value of the external cost of the other pollutants is 50 percent higher than the external cost of climate change. Qualitatively, climate change pollutants are different from other pollutants because the effect is global, rather than local or regional. Which set of external costs are larger is not a concern, however. Both are large, combined they are very large and as we have seen, they can both be addressed by one approach—the 100 percent renewable/distributed/demand-based approach.

Large externalities magnify the impact and importance of other market imperfections, which affect the ability of policy to respond and reduce negative externalities or capture the value of positive externalities. If climate change or other pollutants are recognized as an external cost of energy consumption, they magnify the importance and social cost of failing to address the efficiency gap. This is where the efficiency gap and climate change analyses intersect.

Our review of the conceptual and empirical analysis of the climate change literature shows that the same set of imperfections that affects efficiency also affects the effort to respond to the carbon externality. Therefore, the most important implication of including large externalities is to underscore the need for vigorous policy action to address a problem that is now recognized as larger and more complex. In other words, market failures associated with environmental pollution interact with market failures associated with the innovation and diffusion of new technologies. Thus, as shown in Table 9.1, the combination of substantial market imperfections and large externalities compels the conclusion that there is an urgent need for vigorous policy action.

If market imperfections are routine and the social costs of poor market performance are small (Cell I), modest policies like behavioral nudges may be an adequate response. If market imperfections are small and costs

Table 9.1 Typology of Policy Challenges and Responses

		Magnitude of Total Social Costs	
			Imposes Large Non-productive Macro-economic Costs
		Small	Large
		(I)	(II)
	Routine	Nanny State	Facilitator State
		Behavioral Nudges Information	Infrastructure Demonstration
Extent of Market Barriers & Imperfections			
		(III)	(IV)
	Substantial Barriers Prevent Achievement of Goals	Fixer State Reform Market Social Cost-based Taxes	Developmental State Induced Innovation

Source: Author.

are large (Cell II), then price signals might be sufficient to deal with the externalities. If market imperfections are substantial but costs are small, market reform would be an appropriate response (Cell III), since the slow response and long time needed to overcome inertia would not impose substantial costs. If both market imperfections and social costs are large (Cell IV), more aggressive interventions are in order.

These combined market failures provide a strong rationale for a portfolio of public policies that foster emissions reduction as well as the development and adoption of environmentally beneficial technology. Both theory and empirical evidence suggest that the rate and direction of technological advancement is influenced by market and regulatory incentives that can be cost-effectively harnessed through the use of economic-incentive based policy. In the presence of weak or nonexistent environmental policies, investments in the development and diffusion of new environmentally beneficial technologies are very likely to be less than would be socially desirable. Positive knowledge and adoption spillovers and information problems can further weaken innovation incentives. While environmental technology policy is fraught with difficulties, a view that recognizes the product cycle suggests a strategy of implementing multiple policies as the technology progresses and systematically evaluating both their success and the need to transition to policies that are more appropriate for each phase of diffusion.[1]

In this view, in each cell of the typology in Table 9.1, we identify the role of the state and give an example of the type of policy that is used to perform that role. Faced with major externalities and substantial market imperfection, policymakers should follow the sequence of state activities as described in the analysis of innovation systems. The sequence starts in Cell IV, followed by Cell II, then Cell III, and Cell I.

THE WELFARE ECONOMICS OF VIGOROUS POLICY ACTION

Figure 9.1 presents two views of how the implementation of vigorous policies enhances social welfare. The upper graph is an extension of an analysis by Madrian of the value of bringing behavioral economics into the policy picture. It provides a useful starting point to summarize the welfare economics of our argument because she starts by identifying the benefit of capturing positive externalities, the opposite of the typical approach that launches from negative externalities. She models behavioral barriers that reduce consumer purchases of a good that has a positive externality, that is, the efficiency gap problem. In the upper graph of Figure 9.1, we add market structural and new institutional barriers to the behavioral factors that drive consumer purchases farther from the social optimum. We have constructed the graph to generally reflect the magnitude of effects suggested by the earlier economic analysis and literature.

- Behavioral factors are a modest part of the problem and they affect both consumers and producers.
- Structural and new institutional factors are at least as important as behavioral and they affect both the supply and the demand sides.
- The supply side is at least as important as the demand side.
- The externality market failure is a significant cause of the underinvestment, although smaller than the market structure, institutional, and behavioral barriers.
- The increase in price at the social optimum would be modest because technological progress lowers the supply-side cost, while demand side policies reduce the shift in demand.

In the large distance between the actual equilibrium and the equilibrium that reflects the removal of all barriers, the lower graph of Figure 9.1 also reflects the fact that climate change possesses two characteristics that make it a particularly difficult challenge for traditional neoclassical

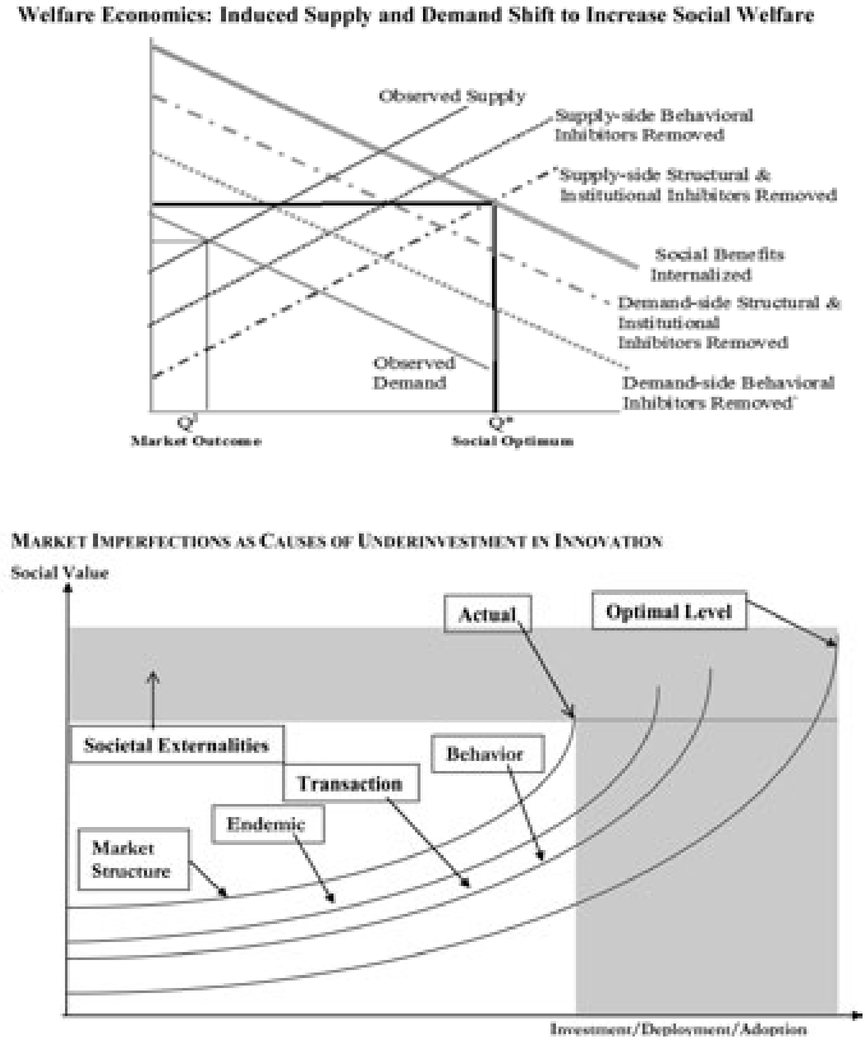


Figure 9.1 Two Views of Market Imperfections and Policy Responses

Sources: Upper graph based on Brigitte C. Madrian, *Applying Insight from Behavioral Economics to Policy Design*, NBER Working Paper No. 20318, July 2014, 7. Lower graph based on Jayant Sathaye and Scott Murtishaw, *Market Failures, Consumer Preferences, and Transaction Costs in Energy Efficiency Purchase Decisions* (California Energy Commission, 2004), 11.

analysis as it has come to be practiced in the United States. Climate change involves very large impacts[2] and a great deal of uncertainty,[3] in part due to the very long time frame of analysis. This raises a host of questions about the discount rate, as discussed below.[4] These characteristics interact to argue for a precautionary principle that supports greater reduction in emissions[5] and the adoption of overlapping policy instruments.[6]

The lower graph of Figure 9.1 presents an investment view of the impact of policies, based on work by analysts at LBNL conducted for the California Energy Commission. The LBNL study identified broad categories of market imperfections, barriers, and obstacles that are important in determining the level of investments—market structure, endemic, transaction cost, behavioral, and externalities. The analysis emphasizes the important role that policy can play in determining where the market will settle. In other words, policy is needed to address the five types of factors that suppress investment in innovative technologies. The challenge is to choose policies that reduce the market barriers in an effective (swift, low-cost) manner.

Given the magnitude and nature of climate change and the extensive nature of market imperfections reinforced by inertia that must be overcome rapidly, each of the policy approaches has a role to play, but the sequence is important. Sequence is important because addressing severe market failures that have large social costs can impose an extraordinary burden on society. The developmental and facilitator role are vital to provide the technical tools to respond to the challenge. Structural change is then critical because it influences how effective the other policies can be.

The findings of this literature can be summarized by noting that policies that successfully overcome market imperfections yield substantial benefits in terms of reducing the cost and accelerating the transition to a low-carbon sector. This was the conclusion drawn in the LBNL analysis of the efficiency gap. The further and faster that foundational and structural changes are implemented, the easier it is for the other policies to work.

- The general finding that the social return from R&D is twice as large as the private return appears to hold in the energy technology space.[7]
- Estimates of the speed of innovation suggest a delay of 1–2 decades in the introduction of new technologies, if targeted policies to accelerate the diffusion of innovation are not adopted.[8]
- Mitigation costs are smaller than adaptation costs,[9] and early action lowers the transitional and total economic cost of decarbonization dramatically,[10] and requires targeted and induced technological change.[11]
- Technology transfer and learning play a vital role in meeting the challenge in a cost effective manner,[12] and targeted financial incentives deliver three times as much monetary support for low-carbon alternatives.[13]
- Because of the magnitude of the transformation required, the macroeconomic impacts of policy take on great significance, with a

smoother, swifter transition projected to yield a very substantial macroeconomic savings of at least 50 percent.[14]

THE ROLE OF PRICE AND PERFORMANCE STANDARDS AS POLICY INSTRUMENTS

Progressive policy has long recognized the limits of price as a policy instrument. This section argues that the performance of price as a policy instrument can only be as good as the market into which the price is introduced. In the case of efficiency and climate change, the underlying market is riddled with imperfections. Price can certainly be a complementary policy, particularly after the important structural changes have been made. In terms of the lifecycle of diffusion, its can make the most positive contribution after alternatives have been developed and are beginning to be widely deployed. The literature supports this conclusion in two ways—the difficulty of defining the discount rate and setting a price on carbon.

The Discount Rate

The market exhibits a high "implicit" discount rate for energy efficiency, which we interpret as the result of the many barriers and imperfections that retard investment in efficiency-enhancing technology.[15] There are several aspects of the high discount rate that deserve separate attention. In a sense, the discount rate is the centerpiece of the market fundamentalist objection to performance standards, but it is based on a view that ignores all the market imperfections that inflate the discount rate. In other words, the claim boils down to the belief that whatever the implicit discount rate the market puts on a decision must be right. Therefore, regulators must be wrong to apply a lower discount rate to justify policy, which implies an economic loss from failing to adopt an energy saving technology to justify policy. Analysis of market imperfections explains the implicitly high discount rate as the result of market imperfections, not consumer preferences.

The empirical evidence on consumer rationality in the literature paints a picture that bears little resemblance to the rational maximizer of neoclassical, market fundamentalist economics. We find a risk-averse,[16] procrastinating consumer,[17] who responds to average, not marginal prices.[18] The consumer is heavily influenced by social pressures,[19] with discount rates that vary depending on a number of factors,[20] and has difficulty making calculations.[21] To make matters more complicated, the consumer does not have control over key decisions. The decision of which energy consuming durable to purchase is made by someone else, like the landlord (that is, the agency problem).[22] Bundles of attributes are decided by producers in circumstances in which the consumer cannot disentangle attributes (the shrouded attributes problem.)[23]

Firms suffer similar problems. We find organizational structure matters a great deal[24] in routine bound,[25] resource strapped organizations[26] confronted with conflicting incentives[27] and a great deal of uncertainty about market formation for new technologies.[28] Knowledge and skill to implement new technologies is lacking[29] and firms have little incentive to create it because of the difficulty of capturing the full value.[30] Public policy efforts to address these problems have been weak and inconsistent.[31] The supply-side does not escape these factors and it exhibits the added problem of powerful vested interests and institutional structures that are resistant, if not adverse, to change.[32]

Given this, it is little wonder that the centerpiece of traditional economic analysis, the discount rate, which is supposed to express the way the utility maximizer maximizes value, is in shambles. Estimates of the discount rate vary widely, from zero to well over 100 percent, and the discount rate appears to be influenced by a wide number of personal and situational factors.[33] In short, we have no solid basis to answer two basic questions:

- How big is the discount rate,[34] especially in the very long-term of climate change?[35]
- How big should it be?[36]

A Price on Carbon

All of the underlying problems that plague the reliance on the discount rate also apply to price. Throughout this analysis, we have not offered or relied on a cost of carbon as a policy for achieving carbon reduction. There is no doubt that recognizing that carbon emissions have massive externalities that impose substantial social costs is critically important to setting the general direction in which the electricity sector must go.

However, we believe that the "cost of carbon" plays little role in the decarbonization policy design. Picking a cost of carbon adds little to the relative attractiveness of low-carbon alternatives[37] and leaves unaddressed the most important policy challenges regarding the best way to navigate toward the goal. At the same time, the difficulty of estimating a cost of carbon adds a great deal of ambiguity to the analysis for several reasons.

First, the precise value of the externality is ambiguous at best. To the extent that setting a price on carbon is left to the market (which is generally preferable to policymakers picking a price), the cost of carbon is "endogenous." It can only be revealed by the technologies that "win" in the marketplace, but the winner of the technology competition is determined not only by price, but also the market structure, transaction costs, behavioral factors, etc. that determines costs and prices. Market imperfections would distort the price signal, much as they distort the implicit discount rate.

While "picking winners" is fraught with dangers, setting the right level of the tax is equally difficult and the benefits of overcoming inertia and other barriers to cost-reducing innovation are large. The futility of picking carbon prices is evident in the incredibly wide range of price projections put forward during the U.S. cap and trade debate in 2007 and 2008.

The National Association of Consumer Utility Advocates commissioned a study that showed the cost of carbon used in the climate change debate exhibited a huge spread—$10/ton to over $100.[38] While those prices remained theoretical, our analysis of proposed nuclear reactors in the Southeastern states of the United States found that an even wider range had been used (as shown in Figure 9.2). Notwithstanding the uncertainty, billions of dollars of construction costs were being paid by consumers based on these estimates.

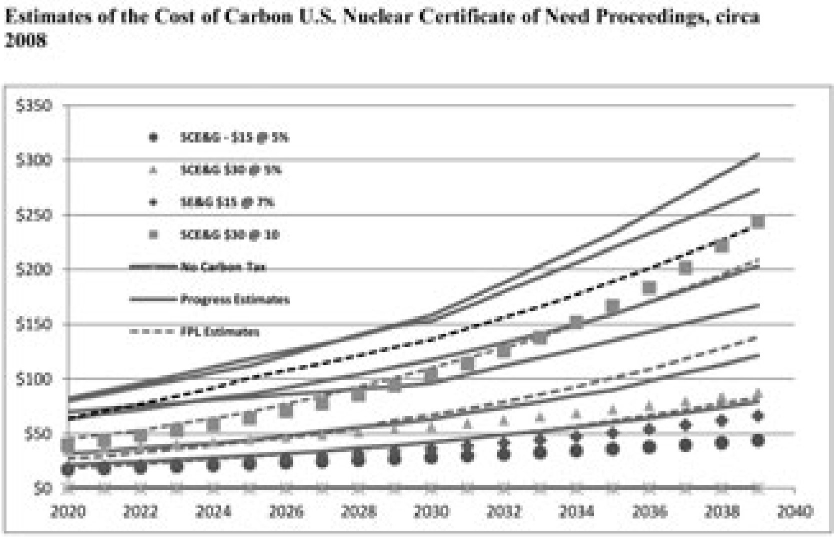


Figure 9.2 The Uncertainty of a Carbon Price

Sources: Mark Cooper, *Advanced Cost Recovery*; Mott MacDonald, *Cost of Low-Carbon Generation Technologies* (Committee on Climate Change, May 2011), Appendix B.

Second, given the complexity of long-term costs and benefits of carbon abatement, it is extremely difficult to know what the optimum tax should be. Moreover, given the large differences in resource costs and other characteristics, the carbon tax is not dispositive of resource selection. Even if one can pick (guess) the right price, that would not eliminate the market perfections. Above all, it would not distinguish between the competing low carbon technologies. The imperfections and inertia would continue to push the market in the wrong direction. The decision to decarbonize dramatically changes the terrain of resource acquisition. However, once the decision is made, externalities are less important and not dispositive of resource selection. The externalities are either neutral or reinforce the conclusion based on the analysis of direct resource cost conclusions.

An analysis by energy researchers at Imperial College moves the theoretical concerns about market imperfections and the problem of setting a price on carbon into the center of the ongoing debate.[39] They start at the theoretical level by cataloguing the very restrictive assumptions that are necessary to reach the conclusion that imposing a hefty tax on carbon is the efficient, first-best way to internalize the carbon externality—perfect, costless information, rational, maximizing behavior, lack of economic market power, frictionless transactions, no political obstacles.[40] They point out that in the energy space, there is a great deal of evidence that demonstrates the simple theory is confronted with and contradicted by a complex reality.[41] The incumbent market and institutional structure is riddled with important and concrete problems that ensure the market outcome will fall short of the theoretical optimum.

The intense interest in the issues of barriers to change and the limitations on price as a policy tool has broken through to the popular press, as demonstrated by a report by Ryan Avent, the Washington-based economic correspondent for the *Economist*. Reporting on "a great session on climate policy"[42] focused on "the environment and directed technical change." Avent noted that it suggested

> Economics is clearly moving beyond the carbon -tax alone position on climate change, which is a good thing. If the world is to reduce emissions, it needs technologies that are both green and cheap enough to be attractive to economically-stressed countries and people. And a carbon tax alone may not generate the necessary innovation. . . . The carbon externality isn't the only relevant externality in the mix. There is another important dynamic in which technological innovation draws on previous research, and so firms are more likely to continue on established innovation trajectories than to start new ones."[43]

About a year later, David Leonhardt, an economic columnist for the *New York Times*, discussed the practical implications of the growing recognition of the challenge of overcoming inertia and closing the "innovation gap."

> To describe the two approaches is to underline their political differences. A cap-and-trade program sets out to make the energy we use more expensive. An investment program aims to make alternative energy less expensive. . . . Most scientists and economists, to be sure, think the best chance for success involves both strategies: if dirty energy remains as cheap as it is today, clean energy will have a much longer road to travel. . . . Still, the clean-energy push has been successful enough to leave many climate advocates believing it is the single best hope. . . . Governments have played a crucial role in financing many of the most important technological inventions of the past century. That's no coincidence: Basic research is often unprofitable. It involves too much failure, and an inventor typically captures only a tiny slice of the profits that flow from a discovery.[44]

POLICY EVALUATIONS: PRICE VERSUS STANDARDS

Framing the issue in this way brings all of the empirical evidence presented with respect to market imperfections and failures to bear on the problem of price as a policy instrument. It indicates that the response to price will fall far short of the predictions of market fundamentalism, or as Nordhaus put it "price fundamentalism." The empirical evidence summarized in Table 9.2 identifies specific studies that address the problem of price. Table 9.2 includes empirical studies in which policies were ranked. In those studies, the price performed poorly, as a general policy, although targeted incentives performed better, but not as well as standards. Evaluations of the effectiveness of policies are overwhelmingly comparative and performance standards rank highly in many of these evaluations. Table 9.4 presents a qualitative evaluation.

Table 9.4 presents the results of an econometric study that gave examples of the broad potential for performance standards to address market imperfection and barriers. The study included a number of measures of the effect of price policy. It derives its hypotheses from a lengthy review of prior empirical studies and compiled a set of panel data covering 39 nations. Representing its findings as confirming earlier analyses and "deciding" some ongoing conflicting interpretations. All of the conclusions support the view taken here. Targeted policies perform much better than

Table 9.2 Empirical Evidence on Policy Directly Evaluating Price in the Climate Change Analysis

Limitations of Markets

Market failures (incumbency, uncertainty, collective action, principle agent, low WTP) (16, 34, 37, 38, 73, 98, 115, 123, 130, 137, D)
Market power (123, 137, ZAD)
Non-market Factor (35, 50, ZO, ZP)
Complex causes of adoption (34, 115, 183, ZZ, ZAC)
Institutional capacity is crucial to effective, least-cost implementation (17, 50, 105, 106, 119, 120, 161)
Technology transfer and learning play a key role (90, 110, 130, D)
Integration: Challenge and Response (5, 13, 18, 54, 56, 58, 114, 138, 139, 199, 201, ZT, ZU)
Inertia v. Urgency (6, 59, 126, 202, F, ZQ)
  Avoid lock in (7, 69, 89, 106, J)
  Early action lowers the transitional and total economic (41, 6, 69, 70, 83, 101, 106)

Evidence on Price and Other Policies

The ineffectiveness of price/ Tax as policy
  Price Insufficiency (4, 11, 15, 19, 20, 25, 29, 63, 70, 81, 82, 102, 144, 160, 188, 191, 193, A, L, S)
  Tax: Difficulty of setting and sustaining "optimal" levels (81, 82, 160, B)
  Tradable permits do not increase innovation (22, 147, 191, C)
Effective Policy Responses (ZR, ZS)
  Public goods (101, 195, ZC)
  Institution Building (90, 94, 110, 195, 195, ZN, ZE)
  Research and Development (22, 57, 82, 97, 101, 102, 103, 106, 130, 141, 148, 188, ZD, ZF)
  Capital subsidies Adders, premium prices (25, 160, ZG, ZY)
  Obligations/Consenting (101, 102, 106, 141, 188, M ZH, ZS, ZAA)
  Standards (44, 90, 100, 171, 172, ZI, ZX)
  Feed in Tariffs (61, 188, Zf, Zz)
  Merit order (27, 67, 85, ZK)
  Flexible, overlapping policies are needed that recognize complexity (17, 81, 125, 126, 130, 152, 169, 179, E, ZV, ZAF)

See Appendix III for sources and notes.

general policies. Standards are particularly effective. Price has mixed effects, at best.

Analysts at LBNL offered a broad view of the impact of performance standards on market, focusing on price as an alternative policy instrument.

> In some cases, the direct regulation of equipment performance might side-step problems of asymmetric information, transaction costs, and

Table 9.3 Evaluation of Policy Instrument for Reducing Greenhouse Gas Emissions from Buildings

Policy	Criteria Effectiveness	Energy/CO_2 Cost Effectiveness	# of Barriers Addressed
Appliance standards	High	High	3
Energy efficiency obligations	High	High	2
DSM	High	High	2
Tax exemptions/reductions	High	High	2
EPC/ESCO	High	Medium/High	3
Building codes	High	Medium	3
Coop. procurement	High	Medium	2
Public leadership programs	Medium/High	High/Medium	4
Labeling and certification programmes	Medium/High	High/Medium	3
Procurement	Medium/High	High/Medium	3
Energy certificates	Medium/High	High/Medium	1
Voluntary/negotiated agreements	Medium/High	Medium	2
Mandatory audit requirement	High/Variable	Medium	1
Public benefit charges	Medium	High	2
Capital subsidies	High	Low	2
Detailed disclosure programs	Medium	Medium	2
Education and information programs	Low/Medium	Medium/high	2
Taxation (on CO_2 or fuels)	Low/Medium	Low	1
Kyoto Protocol flexible	Low	Low	1

Source: Sonja Koeppel, Diana Urge-Vorsatz, and Veronika Czako, *Evaluating Policy Instruments for Reducing Greenhouse Gas Emissions from Buildings: Developed and Developing Countries*, Assessment of Policy Instruments for Reducing Greenhouse Gas Emission from Buildings, Center for Climate Change and Sustainable Energy, Central European University, 2007 Tables 1 and 3.

bounded rationality, obviating the need for individual consumers to make unguided choices between alternative technologies.[45]

Subjective uncertainty, however, may stem from the fact that precise estimates of energy prices and equipment performance are costly

Table 9.4 Policies to Advance Renewable Technologies (Biomass Excluded)

	# of Significant Effects			
Policy	**Pos.**	**Neg.**	**Net Pos.**	**Qualitative Description**
FIT	6	0	6	Particularly successful
Strategic Plan	4	0	4	Strong role
Codes	4	0	4	Supports investment
Allowance	4	−1	3	Mixed
Grant	2	0	2	Effective as short-term measures
Mandates	2	0	2	
Tax Credit	1	0	1	Mixed
Loan	0	0	0	Ineffective
Tax/Price	2	−2	0	Mixed
Infrastructure	0	0	0	Ineffective
Obligations	0	0	0	
Institution	0	−1	−1	
Certificate	0	−2	−2	Ineffective
Local Govt	0	−3	−3	Ineffective

Source: Polzin, Friedmann, et al., "Public Policy Influence on Renewable Energy Investments—A Panel Data Study across OECD Countries," *Energy Policy* 80 (2015): Table 4.

to obtain from the perspective of individual consumers. If the costs of gathering information were pooled across individuals, substantial economies of scale should be achieved which could reduce the uncertainties associated with certain technologies.

The informational requirements that must be met to identify an efficient tax regime, however, are particularly onerous. The government must know not only the level of consumer expectations but also the specific way in which they are formed, and this information must be effectively conveyed to manufacturers through the structure of the tax. In practice, such information may be very difficult to obtain, reducing the efficacy of tax instruments.

Such limitations suggest a potential role for the direct regulation of equipment performance. Energy efficiency standards led to demonstrable improvement in the fuel economy of automobiles in the 1970s and early 1980s. State and local governments set requirements concerning the thermal performance of building elements.[46]

In addition to the ability to adjust the level of the standard, performance standards can provide different functions. A recent description of standards in the diffusion framework underscore this point. Standards are seen as playing different roles at different points in the diffusion process, as noted in Chapter 5.

De la Rue du Can emphasizes qualitative adjustment in the target of the standards.[47] The suggestion that policy in general and standards in particular need to monitor the changing terrain and adapt is evident in the literature in a number of ways.

The barriers addressed include transaction costs, economic uncertainties, lack of technical skill, challenges to technology deployment, inappropriate evaluation of cost efficiency, insufficient and incorrect information on energy features, operational risks, and bounded rationality constraints.

Mechanisms that reduce barriers include information and capacity building by stimulating the demand side; creation and promotion of a stable market; establishment of a methodology for calculating the energy performance of a building; standards on calculation of energy need for heating and cooling. Standards on energy performance rating ensure that there are sufficient incentives. Demand-side stimulation and creation of a functioning efficiency supply market; ensure that qualification, accreditation, and certification schemes are available; and reliable monitoring and diagnostics procedures.

Standards can also be increased as technology develops. Burtraw and Woerman focus on the ability of a standard setting process to evaluate the development of costs and therefore shift the target to capture more benefits. Burtraw and Woerman offered a vigorous defense of well-designed performance standards applying an institutional analysis to the acid rain program. They also cite the recent update of the fuel economy standards as an example.

> Compared to the unintended consequences and complexities of regulation, setting prices to equal the social cost of environmental damages appears simple. Since Pigou (1920), this economic idea has made a large intellectual contribution, yet it has rarely been adopted in environmental policy. One reason that is sometimes offered for the limited influence of environmental prices in environmental policy is the multitude of market failures that prevent a single price from solving the problem. . . . Vested economic interest in the status quo helps to explain institutional inertia and reluctance to change. In any context, a change in the rules will create losers who will act to obstruct such a change, and we invoke this explanation at some

> points. However, we have a more general case in mind where institutions may have strong justifications as solutions to historic problems and serve as watchtowers that protect the precedents of values of previous social decisions. By design or evolution, they affect how change will occur.[48]

While we agree with Burtraw and Woerman in noting the administrative process that allows an adjustment of the level of the standard to new economic conditions, we also emphasize the fact that policies can change the economic conditions. The two go hand in hand.

> The flaw of the SO_2 cap-and-trade program was its inability to adapt to new information that benefits were substantially greater than anticipated and that costs were substantially less. . . . Emissions trading policy for CO_2 in the United States would likely face many of the same issues as SO_2 emissions trading including the inability to update the policy over time. . . .
>
> Differences in institutional structure between a cap-and-trade policy and the Clean Air Act regime cause the regulatory systems to vary in two important ways in how they would react to these changes. One way is the ability to update the emission cap or regulation. If secular or regulatory changes occur that make achieving emissions reductions cheaper and if the cap or regulation is set to approximately equalize marginal costs and marginal benefits, then the availability of cheaper reductions suggests that the cap level or regulation should be tightened to achieve additional reductions. As we have argued, this is unlikely to occur in a timely manner.[49]

FORWARD-LOOKING SUBSIDIES: INERTIA, SUBSIDIES, AND SYSTEM TRANSFORMATION

After putting a price on carbon, the policy that receives the broadest attention and support in the literature is the ones that address the public goods problem. Given the high social rate of return on this investment, the support for this policy is well-founded. Direct subsidies are deemed necessary for basic research and development. As technologies move along the diffusion curve, the need for subsidies declines, but other market imperfections are frequently cited as creating a need for policy intervention. Given the important role of subsidies, early in the development and deployment process, one of the most important battles in the struggle between technologies will inevitably be the struggle over subsidies.

The baseload-dominated electricity system of the 20th century was created by policy support and subsidies for physical and institutional infrastructure that favored a specific type of technology.[50] The dominant incumbents will seek to slow or stop the spread of alternatives to defend these trillion-dollar investments and assets sunk into central station facilities.[51] Recent climate-change analysis highlights how the inertia of a century of domination by central-station, fossil-fuel-focused institutions has created a unique challenge—carbon lock-in—which is magnified by the need to rapidly reduce carbon emissions.

Because the potential external costs are so large and the need to overcome inertia is so great, climate change puts a spotlight on technological innovation. The evidence suggests that the cost of inertia is quite large, whereas targeted approaches that speed and smooth the transition to low carbon resources can have many benefits.[52] The growing concern over adjustment leads to concern over an "innovation gap."[53]

Beyond inertia, many of the benefits of alternative generation technology resources or the processes by which their costs would be reduced—such as learning by doing and network effects—are externalities themselves, which means the private sector will underinvest in them.[54] Returns to R&D can be high.[55] Accelerating innovation can speed the transition, saving a decade or two[56] while reducing economic disruption.[57]

One of the obvious ways to overcome inertia, fill the "innovation gap," and speed the transition is to shift subsidies away from incumbents to the low-carbon alternatives. For example, some have argued that the benefits of stimulating innovation are so large that they can offset the apparent "cost" of phasing out nuclear power altogether.[58]

Our results show that phasing out nuclear power would stimulate investment in R&D and deployment of infant technologies with large learning potentials. This could bring about economic benefits, given the under-provision of innovation due to market failures related to both intertemporal and international externalities.[59]

The evolution of the renewables costs in the coming years will not be independent of the future of nuclear power, as well as of energy and climate policies. In this context of uncertainty, policymakers need to understand the economic consequences of nuclear power scenarios when accounting for its interplay with innovation and cost reduction in renewables.[60]

Analyzing past subsidies strongly supports the proposition that shifting subsidies from nuclear to other resources will lower the cost and accelerate the speed of transition. It strongly rejects the notion that new subsidies should be showered on mature old technologies like aging reactors.[61]

While the nuclear industry complains about the subsidies that are bringing renewables into the market today and resists programs to promote energy efficiency, analysis of the historical pattern demonstrates that the cumulative value of federal subsidies for nuclear power dwarfs the value of subsidies for renewables and efficiency.[62] Renewables are in the early stage of development. Nuclear received much larger subsidies in its developmental stage and enjoyed truly massive subsidies compared to other resources as it grew. There can be debate about the current level of subsidies, particularly given the difficulty of valuing the nuclear insurance and waste subsidies which are existential rather than material (that is, without the socialization of liability and waste disposal the industry would not exist). However, there is no doubt that the long-term subsidization of nuclear power vastly exceeds the subsidization of renewables and efficiency by an order of magnitude of 10 to 1.[63]

While fossil fuels received considerably less subsidy than nuclear, they received an order of magnitude more subsidies than renewables in their early phases. Renewables are more than a dozen years behind the central station resources, but given the importance of inertia, parity may not be enough to overcome the advantages of incumbency.

It is clear that with a much smaller level of subsidy to drive innovation and economies of scale, the renewables have achieved dramatically declining costs in a little over a decade, which is exactly the economic process that has eluded the nuclear industry for half a century.[64] Our analysis of the development of wind and solar, in Chapter 4, reached the same conclusion. The ultimate irony is that despite much smaller subsidies to drive innovation and economies of scale, renewables have achieved dramatically declining costs in just over half a decade, as discussed in Chapter 2.

The dramatic increase in innovative activity despite relatively low levels of R&D subsidy and much lower cumulative subsidization reflects the decentralized nature of innovation in the renewable space. It leads to the dramatic payoff in terms of declining price. As we have seen, wind had the earlier success and solar is now catching up.[65] Nuclear power has failed to show these results because it lacks the necessary characteristics.

First, the nature of the renewable technologies involved affords the opportunity for a great deal of real-world development and demonstration work before it is deployed on a wide scale. This is the antithesis of past nuclear development and the program that SMR advocates have proposed.

Second, the alternatives are moving rapidly along their learning curves, which can be explained by the fact that these technologies actually possess the characteristics that stimulate innovation and allow for the capture of economies of mass production. They involve the production of large numbers of units under conditions of competition. Nuclear power, even SMR technology, involves an extremely small number of units from a very small number of firms, with the monopoly model offered as the best approach.

PERFORMANCE STANDARDS AS AN EXAMPLE OF PROGRESSIVE POLICY

If we take price out of the driver's seat of policy, at least in the early phases of the response, what replaces it? The general analysis of state action showed that direct efforts to stimulate innovations, development and deployment were critical to getting technologies off the ground. However, the market imperfections that retard investment in and adoption of new technologies do not disappear. This section examines one of the most popular and effective nonprice policies—performance standards. As we have described the Paris Agreement, it is essentially a performance standard in two steps. The ultimate goal is to contain the increase in global temperature. Achieving that goal requires a significant and measureable reduction in carbon emissions. A reduction to a specific level over a specified time period is the measure of success. The selection of the method to achieve that reduction is open. The individual nations are allowed, even encouraged, to achieve their goals in the manner that suits them best. Discipline will be implemented by transparency and collaboration.

Performance standards should be among the first tools added to the policy portfolio because they can readily be designed as "command but not control." They are a structural intervention that addresses more market imperfections and barriers than other policies, are more effective in overcoming them, and are more likely to achieve their goals. As shown in the upper part of Table 9.5, the ability of performance standards to address market failure problems goes beyond their ability to address the barriers to investment in efficiency-enhancing technologies that focus on consumer behavioral and transaction cost economics. Standards can also address the behavioral and transaction cost problems that afflict the supply-side of the market, as well as some of the structural problems.[66]

At the outset, it is important to be clear about what we mean by "command but not control." While the empirical research supports a broad view of evolving standards, it also supports the conclusion that there is a need to take into account behavioral factors[67] and the interaction between standards and complementary policies.[68] Therefore, standards must really command, but not control, thereby unleashing the forces of innovation and competition in the market economy. The lower part of Table 9.5

Table 9.5 Market Imperfections and Performance Standards

Causes of Market Failure Addressed by Standards

Traditional	Transaction Costs/ Institutional	Endemic Flaws
Societal Failures	Sunk Costs	Agency
Externalities	Risk	Asymmetric Information
Information	Uncertainty	**Moral Hazard**
Structural Problems	Imperfect	Behavioral Factors
Scale	Information	Motivation
Bundling		Calculation/ Discounting
Cost Structure		
Product Cycle		
Availability		

Key Design Features of Effective Performance Standards

Technology-Neutral: Taking a technology-neutral approach to the long-term standard unleashes competition around the standard that ensures that consumers get a wide range of choices at that lowest cost possible, given the level of the standard.

Product-Neutral: Attribute-based standards accommodate consumer preferences and allow producers flexibility in meeting the overall standard.

Pro-Competitive: All of the above characteristics make the standards pro-competitive. Producers have strong incentives to compete around the standards to achieve them in the least-cost manner, while targeting the market segments they prefer to serve.

Long-Term: Setting an increasingly rigorous standard over a number of years that covers several redesign periods fosters and supports a long-term perspective. The long-term view lowers the risk and allows producers to retool their plants and provides time to re-educate the consumer.

Responsive to industry needs: Recognizing the need to keep the target levels in touch with reality, the goals should be progressive and moderately aggressive, set at a level that is clearly beneficial and achievable.

Responsive to consumer needs: The approach to standards should be consumer-friendly and facilitate compliance. The attribute-based approach ensures that the standards do not require radical changes in the available products or the product features that will be available to consumers.

Source: Mark Cooper, *Energy Efficiency Performance Standards: The Cornerstone of Consumer-Friendly Energy Policy*, Consumer Federation of America, October 2013.

identifies the characteristics associated with effective standards. The key point about performance standards is they establish a minimum level of efficiency, but they do not dictate the technology.

Our analysis shows that performance standards work best when they address clear market imperfections that lead to market failure. They work best when they are technology-neutral, product-neutral, and procompetitive. Producers can design and deploy products to meet the standard as they see fit. They will do so by choosing the least-cost approach available to them. Different producers will have different skill sets or different product lines and choose different technologies. Well-designed performance standards give the market certainty to stimulate adoption of cost-effective energy-saving technologies. Standards must also be reasonable in relationship to what can be technologically accomplished. If standards go too far, impose costs that are too large, or require technologies that cannot be developed or delivered in the necessary time frame, they can do unnecessary harm, rather than good.

Impact of Standards on Efficiency

Analyses that fail to take into account the powerful process of technological innovation will overestimate costs, undervalue innovation, and perpetuate market failure. Detailed analyses of major consumer durables—including vehicles, air conditioners, and refrigerators—find that technological change and pricing strategies of producers lower the cost of increasing efficiency in response to standards.

One of the strongest findings of the empirical literature is its support of the theoretical expectation that technological innovation will drive down the cost of improving energy efficiency and reducing greenhouse gas emissions. The comprehensive review in *Technology Learning in the Energy Sector* found that energy efficiency technologies are particularly sensitive to learning effects and policy.

> For demand-side technologies the experience curve approach also seems applicable to measure autonomous energy efficiency improvements. Interestingly, we do find strong indications that in this case, policy can bend down (at least temporarily) the experience curve and increase the speed with which energy efficiency improvements are implemented.[69]

1. For the past several decades, the retail price of appliances has been steadily falling while efficiency has been increasing.

2. Past retail price predictions made by the DOE [U.S. Department of Energy] analysis of efficiency standards, assuming constant price over time, have tended to overestimate retail prices.
3. The average incremental price to increase appliance efficiency has declined over time. DOE technical support documents have typically overestimated the incremental price and retail prices.
4. Changes in retail markups and economies of scale in production of more efficient appliances may have contributed to declines in prices of efficiency appliances.[70]

Sperling et al. reach a similar conclusion.

> The more specific point here is that, while regulatory compliance costs have been substantial and influential, they have not played a significant role in the pricing of vehicles. . . .
>
> As with any new products or technologies, with time and experience, engineers learn to design the products to use less space, operate more efficiently, use less material, and facilitate manufacturing. They also learn to build factories in ways that reduce manufacturing cost. This has been the experience with semiconductors, computers, cellphones, DVD players, microwave ovens—and also catalytic converters.
>
> Experience curves, sometimes referred to as "learning curves," are a useful analytical construct for understanding the magnitude of these improvements. Analysts have long observed that products show a consistent pattern of cost reduction with increases in cumulative production volume. . . .
>
> In the case of emissions, learning improvements have been so substantial, as indicated earlier, that emission control costs per vehicle (for gasoline internal combustion engine vehicles) are no greater, and possibly less, than they were in the early 1980s, when emission reductions were far less.[71]

A comparative study of European, Japanese, and American automakers, prepared in 2006 before the recent reform and reinvigoration of the U.S. fuel economy program, found that standards had an effect on technological innovation. The United States had lagged because of a dormant U.S. standards program and the fact that U.S. automakers did not compete in the world market for sales (that is, it did not export vehicles to Europe or Japan, where efficiency was improving).[72]

The track record of efficiency standards for household consumer durables in general is excellent[73] The record of four consumer durables since the late 1980s has been intensely studied. Data on the efficiency of these devices has been compiled since then, which covers the period in which natural gas prices were deregulated. While the efficiency was increasing, the cost of the durables was not. Five standards were introduced for the four appliances. In three of the cases—refrigerators, clothes driers (second standard), and room air conditioners—there was a slight increase with the implementation of the standard, then a return to pre-standard downward trend. In one case—clothes driers (first standard)—there was no apparent change in the pricing pattern. In one case (central air conditioners), there was an upward trend, which may be explained by a surge in metal prices during that period.

We examined the track record in detail, building a cross-product multivariate regression analysis covering five important household appliances. Since the ability to transform consumption plays an important part in long-term decarbonization, this track record is quite enlightening.

We have constructed the analysis in the typical way. The dependent variable is energy consumption with the base year set equal to 1. Later years have lower values. Similarly, the difference between appliances is handled with dummy variables. We include each appliance except furnaces, which shows how the other appliance performed compared to furnaces, whose standards were largely stagnant over the period. A negative number means that the other appliances had lower levels of energy consumption. A variable is introduced to represent the adoption of a standard. This variable (known as a dummy variable) takes the value of 1 in every year when the standard was in place and a value of zero when it was not. A negative number means that the years in which the standard was in force had lower levels of energy consumption.

Table 9.6 shows the results of econometric analysis of the data underlying Figure 9.2. It shows that stricter standards lead to measurable improvements in appliance efficiency—is statistically valid when rigorous controls are introduced into multivariate regression analysis. measure the trend of efficiency improvements by including the year as trend term.

The impact of standards is statistically significant and quantitatively meaningful in all cases. The coefficient in column 6 (All Years, All Variables) indicates that the standard lowers the energy consumption by about 8 percent. This finding is statistically significant, with a probability level less than 0.0001. There is a very high probability that the effect observed is real.

The underlying trend is also statistically significant, suggesting that the efficiency of these consumer durables was improving at the rate of 1.35 percent per year. Given that the engineering-economic analysis had justified the adoption of standards and that standards were effective in

Table 9.6 Multivariate Analysis of Standards

Variable	**Statistic**	**5 Years Before/After**			**All Years**		
		1	**2**	**3**	**4**	**5**	**6**
Standard	β	−.1637	−.1386	−.1086	−.2260	−.1079	−.0803
	Std. Err.	(.0485)	(.0587)	(.0382)	(.0366)	(.0414)	(.0227)
	p <	.000	.023	.007	.000	.010	.001
Trend	β	NA	−.0053	−.0111	NA	−.0107	−.0135
	Std. Err.		(.0081)	(.008)		(.0026)	(.0019)
	p <		.51	.176		.000	.000
Refrig	β	NA	NA	−.2775	NA	NA	−.2242
	Std. Err.			(.0382)			(.0289)
	p <			.000			.000
Washer	β	NA	NA	−.2889	NA	NA	−.2144
	Std. Err.			(.0561)			(.0391)
	p <			.000			.000
RoomAC	β	NA	NA	.0478	NA	NA	−.0895
	Std. Err.			(.0642)			(.0321)
	p <			.383			.009
CAC	β	NA	NA	−.0050	NA	NA	.0383
	Std. Err.			(.0292)			(.0260)
	p <			.864			.143
R^2	**.20**	**.21**		**.85**	**.29**	**.36**	**.75**

Sources: Statistics Beta coefficient and robust standard errors. Steven Nadel and Andrew deLaski, *Appliance Standards: Comparing Predicted and Observed Prices*, Research Report E13D, ACEEE, 2013.

lowering energy consumption, this means the market trend was not sufficient to drive investment in efficiency to the optimal level

Comparing the models with shorter terms to the All Years model we find the impact of the standard is greater (almost 11 percent in column 3) because we have eliminated the out-years where the effect of the standard has worn off. The impact of the trend is slightly smaller (1.1 percent per year) but the statistical significance is greatly affected by shortening the period because we truncate the trend.

We do not mean to suggest that the price increases were too big compared to the engineering-economic analysis or that the standards lowered costs, although there are theories that would support such conclusions (that is, that suppliers take the opportunity of having to upgrade energy efficiency through redesign to make other changes that they might not have made). However, this does indicate that the standards can be implemented without having a major, negative impact on the market. The analysis of consumer durables also shows that there was no reduction in the quality or traits of the products. The functionalities were preserved while efficiency was enhanced at modest cost.

Examining the trends for individual consumer durables suggests three important observations.

- First, the implementation of standards improved the efficiency of consumer durables.
- Second, costs decline as producers develop technologies to meet the standard.
- Third, after the initial implementation of a standard, the improvement levels off, suggesting that if engineering-economic analysis indicates that improvements in efficiency would benefit consumers, the standards should be strengthened on an ongoing basis.

PROGRESSIVE POLICY AND REGULATION

Capitalist industrial societies have long wrestled with how to deploy and operate vital infrastructure. For over 100 years the progressive capitalist paradigm in the United States drove nondiscriminatory access, seamless interconnection, and universal service for basic utilities. In most other industrial nations, it was deployed as a state-owned monopoly. In the United States, however, it was deployed as a regulated private franchise monopoly.[74] The United States chose to use private capital subject to oversight and public interest obligations to provision those networks, and pubic supply where private capital would not go, creating a hybrid model with a small public sector.

Table 9.7 presents three examples of general principles. We have discussed the Scherer and Ross approach in Chapter 4. Here we focus on the framework offered by Hepburn.

As noted above, Burtraw and Woerman point to the analysis of Hepburn as demonstrating why price has serious flaws as a policy instrument.

> One reason that is sometimes offered for the limited influence of environmental prices in environmental policy is the multitude of

Table 9.7 Principles and Practice for Regulation in Progressive Capitalism

Scherer and Ross on "Good Market Performance"	Hepburn, Government, the Market, and Environmental Policy	Stiglitz, Principles for Productive Taxation
Be efficient: Not waste scarce resources	Address imperfection of price, externalize non-marginal effects, recognize complex uncertainty, engage in market creation	Tax to improve efficiency
Be responsiveness to consumer demand	Recognize unwillingness to pay	Tax things that don't disappear when taxed
Not allow excess profits	Tax bads, recognize unwillingness to pay Control rent seeking by market and gov't.	Tax worse, not better, things Tax to reduce monopoly profits and rents Close tax loopholes
Progressive: Taking advantage of opportunities opened by science and technology to increase output contributing to long-run growth of real per capita income & provide consumers with superior new products.	Subsidize R&D, promote coordination Provide infrastructure	Tax to improve incentives to stimulate investment Tax to raise money for social purposes
Equitable distribution of income	Address principle agent problems Be impartial, stable, and risk-aware Promote quality administration of rules	Tax progressively to improve the distribution of income
Facilitate stable full employment resources, especially human resources		Tax to improve incentives to stimulate creation of jobs

Sources: Cameron Hepburn, "Environmental Policy, Government, and the Market." *Oxford Review of Economic Policy* 26 (2010): 117–136; Scherer, Frederic M., and David Ross. *Industrial Market Structure and Economic Performance* (3rd ed.). Boston, MA: Houghton Mifflin, 1990; Joseph E. Stiglitz, "Phony Capitalism." *Harper's Magazine*, September 2014.

> market failures that prevent a single price from solving the problem. . . . This paper argues that another reason for limited influence is the failure to anticipate the institutional context in which economic ideas will take shape. We use the term institutions broadly to describe the set of laws, rules, organizations and relationships that pre-exist a policy intervention; that is, features of the empirical context of a policy problem.[75]

Hepburn's analysis includes very strong statements on the inadequacy of price,[76] especially when confronted with a major externality like climate change.

> Frequently, prices can serve as powerful coordinating device, because they transmit information so efficiently. However, this also causes problems if prices are transmitting the wrong information because markets are distorted in some way. . . . While a carbon price, delivered by a carbon market, may well be a necessary component of successful climate-change policy, complementary government interventions are also likely to be required.[77]
>
> For extremely simple environmental problems, it might be enough just to get the prices right (or at least less wrong). For climate change, even getting carbon prices right would not be enough—there are too many other market failures, the investment requirements are too long term, the investments are nonmarginal, and international political economy considerations are critical.[78]

The Hepburn article contains a great deal more, which parallels the arguments made in this book. Hepburn starts from the premise that values are the starting point for policy analysis, "Approaches to environmental protection, like other policy areas, reflect the prevailing value judgements about the role and size of the state."[79] He rejects the market as the solution and the narrow,[80] "night watchman" role for the state, citing the continuing and expanding role of the state: "government involvement in the economy has climbed to record highs in recent years, with the state playing a more comprehensive role in providing social security, education, physical and mental health, and in other resource-allocation decisions."[81] He observes the ebb and flow of policy in the reaction to the slowdown of the late maturity phase of the second industrial revolution[82] and the important role of the financial meltdown in shaking the faith in the efficient market hypothesis.[83] He ties these historical developments to the more progressive approach to climate policy.

> The crisis has also created doubts about market-based approaches to environmental problems. At the international level, climate-change policy appears to be moving from being predominantly market-based. . . to a mixed system which includes a role for national planning, a focus on 'nationally appropriate mitigation actions' for developing countries, and the actions in the Copenhagen Accord.[84]

He identifies a series of important market failures that must be addressed, including public goods (such as the military), infrastructure, information, coordination, principle agent (rent seeking), and perverse incentives supported by inaccurate and inappropriate accounting. Policy is necessary to address these, but the state has significant limitations in its ability to do so, particularly in its inability to sustain the "evolutionary dynamic that generates diversity and wealth."[85] The solution lies in command but not control, with the state setting the overall objectives and leaving it to the market to deliver.

His solution is essentially what we call pragmatic progressive capitalism.

> On the one hand, leaving environmental protection to the free market, relying on notions of corporate social responsibility and altruistic consumer and shareholder preferences, will not deliver optimal results. On the other hand, nationalizing the delivery of environmental protection is likely to fail because nation states rarely have the depth and quality of information required to instruct all the relevant agents to make appropriate decisions. Thus, as for many areas of policy, appropriate models of environmental intervention will lie between these two extremes.[86]

These principles are embodied in Stiglitz's critique of simple-minded "soak the rich" taxes, which underscores the broad scope of progressive principles. "A well designed tax system can do more than just raise money—it can be used to improve economic efficiency and reduce inequality."[87]

As shown in Table 9.7, Stiglitz argues that tax policy can be used to accomplish a number of goals beyond reducing inequality and raising revenue, including improving efficiency by reducing monopoly rents, discouraging harmful behaviors/encouraging beneficial behaviors, and stimulating investment and job creation. Efficiency is improved when taxes reduce monopoly profits and rents, provide incentives to invest and create jobs, and generally fall heavier on "bad" things than "good." Equity is served with progressive taxes, closing loopholes, and creation of jobs.[88] Price, like taxation, should be a refined, not a blunt instrument.

> Taken together, these proposals would make real inroads into reducing inequality, returning us to an economy more like that of the post-war years. Those were the years when America was becoming the middle-class society it had long professed to be, with decades of rapid growth and widely shared prosperity, when those at the bottom saw their incomes grow faster than those at the top. They are also the years that Thomas Piketty views as an anomaly in the history of capitalism. But getting back to that time doesn't require eliminating capitalism; it requires eliminating the market distortions of the ersatz capitalism practiced in this country today. This is less about economics than it is about politics. We don't have to choose between capitalism and fairness. We must choose both.[89]

This nuanced economic approach is necessary for several reasons. First, there are some people who cannot afford service, so a subsidy is necessary to achieve universal service. Second, you have to pick the level of service and the price must cover the costs of the network, otherwise you end up with poor service. Third, the higher the level of service, the higher the cost and larger the number of consumers who are hurt because they are denied access to a service that meets their needs without all the bells and whistles. Fourth, the current technology is never all we need; we want a dynamic, innovative space that continues the development and deployment of new technologies. Therefore, the economy still needs effective markets to drive innovation and deployment.

The progressive approach recognizes the many sources of market failure and rejects the *laissez faire* approach from top to bottom. The successful U.S. model was pragmatic, progressive capitalism that recognized the economics of network industries. The economics of networks is recognized in pragmatically progressive policy.

- It controls excess profits.
- It recovers costs from the most discretionary services by allocating joint and common costs to more discretionary services defined by the perceived social value of the service and the pragmatic ability to recover costs.
- It recovers subsidies in a manner that causes the least distortion to demand for basic service (taxes on discretionary services, line items on the bottom of the bill that can easily be erased for the subsidy recipients, or nonbill transfers).
- It subjects joint cost recovery and subsidy taxation to a stand-alone cost constraint, which is a moving target. When luxury or business users can credibly threaten to bypass the network, they are enticed

to stay on as long as the rates make the maximum possible contribution to the joint and common costs.

The progressive approach forcefully rejects the *laissez faire* welfare economic assumptions:

- Utility is not equated with well-being.
- The marginal value of an additional dollar of income is not assumed to be constant all the way down the income distribution.
- The distribution of surplus between producers and consumers, or even among consumers, matters a great deal.

On the supply-side, infrastructure networks are costly and different users and uses impose costs on the network. On the demand-side, the value of functions varies between users who exhibit differences in their willingness and ability to pay for services. In response to basic network economics, it was sensible to recover costs from the cost-causers to the extent possible and practical to create customer classes defined by significant differences in usage traits, and to differentiate services between and within classes. Ironically, while the world has migrated to the U.S. model, the United States itself has moved away from the balance between the public and private sector, which served well for a half-century after the New Deal legislation. Starting in the 1980s, the balance was upset by a shift that strongly favored private interests in the hope that removing barriers to entry would trigger vigorous competition. The results have been spotty at best.

10

DECISION MAKING AND THE TERRAIN OF KNOWLEDGE

INTRODUCTION

The selection of technologies and resources to meet the need for electricity has always been a complex task, involving many factors like price, reliability, security of supply, and environmental and public health impacts, as noted in Chapter 7.[1] However, over the past quarter century two changes in the decision-making environment have made the task much more complex—volatile fossil-fuel prices and concerns about climate change. As a result, the resources that accounted for the vast majority of electricity generation for almost a century have become far more risky and costly and far less attractive. At the very same moment, the need for electricity is expanding to serve billions of people who are underserved or unserved and to meet the needs for increasing electrification of the digital political economy. The search is on for alternatives and the central role of electricity in a 21st century economy gives the search extreme urgency.

The pressing need for new resources also has stimulated a second search: an effort to develop decision-making tools that can cope with the increasingly complex and ambiguous nature of technology/resource selection. Calls for new approaches that involve "weighing the risks of climate change"[2] and "practicing risk-aware . . . utility resource selection"[3] abound,[4] but most of these efforts fail to actually offer a comprehensive decision-making framework. Instead, they jump to subjective and *ad hoc* evaluations of alternatives.

In this chapter, we seek to advance the transition to a new decision-making approach based on the central premise that the key insights needed for effective public policy will not come solely or even primarily from tweaking cost estimates to make more accurate projections, as was done in Part III of this book. Good cost estimation is important, but only part of the solution. Because the factors that affect future prices are complex and the outcomes are ambiguous, there is a need for a framework for decision making that identifies the major sources of ambiguity and suggests policies that can deal with them.

The following discussion seeks to smooth the transition to a new framework in two ways. First, we note that decision makers in fields as diverse as financial portfolio analysis,[5] project management,[6] technology risk assessment,[7] Black Swan Theory,[8] military strategy,[9] and space exploration[10] have developed remarkably similar analytic tools and principles for navigating in their complex, ambiguous environments. Widespread adoption of this approach in society suggests that decision makers in the electricity sector can have confidence that this is a prudent approach. The calls for and efforts to develop a new way of thinking to make changes understandable and behaviors coherent across a number of fields is indicative of the turning point in the development of the political economy. This new "common sense" also reflects the extremely complex and integrated nature of the emerging energy and economic systems.

Second, we seek to make the shift to a new decision-making framework manageable by demonstrating the framework with data that decision makers traditionally use in making their technology/resource selections. The proposed operationalization of the concepts rests on simple mathematics[11] applied to the data analyzed in Part III to develop incremental, empirical steps toward the new framework.

THE COMPLEX TERRAIN OF KNOWLEDGE

Over the past half century decision makers in a variety of fields have developed a number of analytic tools and investment strategies to deal with the ambiguity that affects decision making, including broad frameworks that map the terrain of knowledge into four regions. The effort to map the terrain of knowledge starts from the premise that there are two primary sources of ambiguity.[12] Decision makers may lack knowledge about the nature of outcomes and/or they may lack knowledge about the probabilities of those outcomes. As shown in Table 10.1, four regions of knowledge result from this basic analytic scheme: risk, uncertainty, vagueness, and unknowns. Each region of knowledge presents a distinct challenge to the decision maker.

The purpose of the framework is to identify the characteristics of each region, the analytic tools that are best suited to exploring it, and the policy tools that are best able to deal with the state of knowledge in the region. The integrated approach (Table 10.2) allows the decision maker

Table 10.1 Ambiguity Defined by Four Regions of Knowledge

	Knowledge of Nature of Outcomes	
	Low	**High**
High	**Vagueness:** **Condition:** The decision maker may not be able to clearly identify the outcomes, but knows the system will fluctuate. **Strategy: Fuzzy Logic** **Action:** Avoid long-term paths that are least controllable. Minimize surprises by avoiding assets that have unknown effects. Create systems that can monitor conditions and adapt to change to maintain system performance.	**Risk:** **Condition:** The decision maker can clearly describe the outcomes and attach probabilities to them. **Strategy: Hedge** **Action:** Identify the trade-offs between cost and risk. Spread risk by acquiring assets that are uncorrelated (do not overlap).
Knowledge of Probabilities of Outcomes		
Low	**Unknowns:** **Condition:** In the most challenging situation, knowledge of the nature of the outcomes and the probabilities is limited. **Strategy: Diversity & Insurance** **Action:** Buy insurance to build resilience with diverse and redundant assets. Diversity requires increasing the variety, balance, and disparity of assets. Fail small and early. Avoid relying on low-probability positive outcomes and betting against catastrophic negative outcomes.	**Uncertainty**: **Condition:** The decision maker can clearly describe the outcomes but cannot attach probabilities to them. **Strategy: Real Options** **Action:** Buy time to reduce exposure to uncertainty by choosing sequences of hedges that preserve the most options. Acquire small assets with short lead times and easy exit opportunities.

Source: Author.

Table 10.2 Mapping and Exploring the Terrain of Knowledge

Features	**Regions of Knowledge**			
Topography	**Unknowns**	**Vagueness**	**Uncertainty**	**Risk**
Technology Risk Assessment				
Challenges	Unanticipated effects	Contested framing	Nonlinear systems	Familiar systems
Outcomes	Unclear	Unclear	Clear	Clear
Probabilities	Unpredictable	Predictable	Unpredictable	Predictable
Black Swan Theory				
Challenges	Black Swans Wild randomness	Sort of safe	Safe	Extremely safe Mild randomness
Conditions	Extremely fragile	Quite robust	Quite robust	Extremely robust
Distributions	Fat-tailed	Thin-tailed	Fat-tailed	Thin-tailed
Payoffs	Complex	Complex	Simple	Simple
Project and Risk Mitigation Management				
Challenges	Chaos	Unforeseen uncertainty	Foreseen uncertainty	Variation
Navigation Devices				
Framework	Multi-criteria analysis	Fuzzy logic	Decision heuristics	Statistics
Analysis	Diversity assessment	Sensitivity analysis	Scenario analysis	Portfolio evaluation
Focus	Internal resources & structure	Internal resources & structure	External challenges	External challenges

Navigational Principles

	Learning	Adapting	Planning	Controlling
Processes	Learning	Adapting	Planning	Controlling
Instruments	Insurance/diversity	Monitor & Adjust	Optionality	Hedging

Advice	Technology Risk Assessment
	Precaution
	Buy Insurance
	Accept Non-optimization
	Diversity
	  Variety
	  Balance
	  Disparity
	Black Swan Theory
	Truncate Exposure
	Buy Insurance
	Accept Non-optimization
	Redundancy
	  Numerical
	  Functional
	  Adaptive
		Technology Risk Assessment
		Resilience
		Adaptability
		Black Swan Theory
		Multi-functionality
		What Works
			Technology Risk Assessment
			Flexibility
			  Across Time
			  Across Space
			Black Swan Theory
			Optionality
				Technology Risk Assessment
				Resilience
				Robustness
				Hedge
				Black Swan Theory
				Robust to Error
				Small, Confined, Early Mistakes
				Incentive & Disincentives
				Avoid Moral Hazard
				Hedge

Sources: Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable* (New York: Random House, 2007), Postscript; Andrew Stirling, *On Science and Precaution in the Management of Technological Risk*, European Science and Technology Observatory, 2001, 17; *On the Economics and Analysis of Diversity*, SPRU Paper No. 28, University of Sussex, 2000, Chapter 2; "Risk, Precaution and Science: Towards a More Constructive Policy Debate," *EMBO Reports* 8 (2007); David A. Maluf, Yuri O. Gawdisk, and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety, NASA Technical Reports, 2005*; Gene B. Alleman, *Five Easy Pieces of Risk Management,* May 8, 2005. See also, Arnoud De Meyer, Christopher H. Lock, and Michel T. Pich, "Managing Project Uncertainty: From Variation to Chaos," *MIT Sloan Management Review,* Winter (2002); Alan D. Campden, "Cyberspace Spawns a New Fog of War," *SIGNAL Magazine,* September 2010; Eric Bland, 2010, "Fog of War Demystified by Financial 'Power Law,'" *Discovery News*, January 7, 2010.

to array the options under consideration in a multiattribute space. The topographic features show the primary challenge created by the conditions in the region. Three different ways of characterizing the regions are offered: technology risk assessment, Black Swan Theory, and project and risk mitigation/management. Under the navigational devices, we include the analytic approaches and tools, as well as the data that are used in the analysis. The policy tools and rules are grouped according to the regions for which they are best suited, but they should be viewed as a mutually reinforcing global set of principles.

These frameworks arrive at a similar mapping of the terrain of knowledge and policy rules for coping with a lack of knowledge because they share a fundamental critique of the statistical models used in much predictive analysis. Statistical models are essentially useless for predicting rare events because the assumptions about frequencies or distributions necessary to build the models do not fit the reality of rare events. The application of inappropriate statistical models to predict improperly defined outcomes increases the exposure to rare events (surprise) because model builders "don't know what they don't know," and therefore, they do not take the proper precautions against rare events. More broadly, the narrow optimization approach that flows from the statistical models that dominate economics increases the risk of harm from surprise negative (black swans) because it produces social structures (organizations, institutions) that are overly specialized and unable to adapt to perturbation in their environment.

The contemporary critique focuses heavily on the overreliance on probabilities, which are suited to only one of the four regions. Technology Risk Assessment frames this issue as follows: simplification of complex outcomes "can have explosive consequences since it rules out some sources of uncertainty; it drives us to misunderstanding the fabric of the world."[13] Here there is a direct link to Knightian/Keynesian uncertainty that was identified earlier as an important part of the critique of the neoclassical/*laissez faire* model of capitalism noted in Chapter 2. We will next briefly describe the original formulations of the approach in each of the schools as background for our synthesis. The intellectual origins of the three broad approaches are identified in Table 10.2.

> Unfortunately, exclusively "realist" or "frequentist" probabilistic understandings of incertitude are open to serious doubts concerning the comparability of past and future circumstances and outcomes. The concept of a hypothetical series of trials is singularly inappropriate in cases where the decisions in question are large in scale or essentially unique, take place in a complex and rapidly changing environment or involve effectively irreversible impacts. Where the

> different aspects of performance are many in number and incommensurable in form, attempts to reduce this to a single metric further compound the difficulties. In disciplines such as financial investment appraisal, the existence of short time horizons and a dominating monetary "bottom line" are often held to supersede such difficulties and justify the imposition of a single numeraire. Yet in fields such as industrial strategy, policy analysis and technology assessment, these issues of scale, novelty, uniqueness, complexity, change, irreversibility an incommensurability are manifestly the norm and cannot be readily set aside. In a strict "frequentist" sense, then, techniques based on probability theory are quite simply inapplicable to many of the most important decision that take place within the economy. In these contexts at least . . . probability does not exist.[14]

Black Swan Theory argues that rare events have a huge impact on the development of daily life, but that these events are inherently unpredictable and humans have difficulty dealing with them.[15] The increasing importance of rare evens stems from the nature of the modern world.

> Our modern, complex, and increasingly recursive world . . . means that the world in which we live has an increasing number of feedback loops, causing events to be the cause of more events, thus generating snowballs and arbitrary unpredictable planet-wide winner-take all effects. We live in an environment where information flows too rapidly, accelerating epidemics. Likewise, events can happen because they are not supposed to happen.[16]

A related second characteristic of the modern world that increases the importance of rare events is their viral nature, which results in scalability—the tendency for impacts to spread widely.

> Those who start, for some reason, getting some attention can quickly reach more minds than others and displace the competitors.[17]
>
> Fads will be more acute, so will runs on banks . . . a very strange virus spreading throughout the planet.[18]

Technology risk assessment frames the challenge similarly. "Knowing your ignorance is the best part of knowledge."[19] It rejects "the authority of [a] 'risk-based' approach," based on an "appeal to monolithic notions of methodological rigour and on the unitary nature of the analytical results thereby obtained."[20] This stance is compatible with the critique of neoclassical economics discussed in Chapter 3.

> Risk is conventionally regarded to comprise the two basic elements of probabilities and magnitudes. . . . Risk is a condition under which it is possible both to define a comprehensive set of all possible outcomes *and* to resolve a discrete set of probabilities (or a density function) across this array of outcome. The strict sense of the term *uncertainty*, by contrast, applies to a condition under which there is confidence in the completeness of the set of outcomes, but where there is acknowledged to exist no valid theoretical or empirical basis for the assigning of probabilities to these outcomes. . . . The condition of "fuzziness," under which the various possible outcomes do not admit of discrete definition. Finally, there is the condition of *ignorance*. This applies in circumstances where there not only exists no basis for the assigning of probabilities (as under uncertainty), but where the definition of a complete set of outcome is also problematic.[21]

INTELLECTUAL ORIGINS OF THE ANALYSIS OF AMBIGUITY

In this section, we briefly describe the three approaches to describing the terrain of knowledge with citations to the original literature. This is by no means intended to be a comprehensive review. Our goal is to provide some additional depth and support for our characterization of the four regions of knowledge.

Black Swan Theory

In Table 10.3, which reproduces the original framing from Black Swan Theory, we find that the dimensions are presented as decreasing levels of knowledge. They run from highest to lowest knowledge; this is the case with all three of the approaches discussed here. In our approach to the analysis, the decision-making space is darkest near the origin where knowledge is lacking. We think a good way to characterize the endeavor of policy, regulatory and financial analysts is to shed a little more light on the decision-making environment so that we can navigate better in and expand the regions of partial knowledge, and avoid harmful surprises.

As shown in Table10.3, Black Swan Theory is most concerned about areas where complex payoffs interact with limited knowledge of probabilities. Instead of focusing on gaining more precise knowledge about what is predictable, Black Swan Theory argues we need to gain a better understanding of what is unpredictable.

> Black Swans being unpredictable, we need to adjust to their existence (rather than naively try to predict them). There are so many

Table 10.3 Framing the Terrain of Knowledge: Black Swan Theory

	Application	
Domain	Simple payoffs	Complex Payoffs
Distribution 1 ("thin" tailed)	Extremely robust to Black Swans	Quite robust to Black Swans
Distribution 2 ("heavy" and/or unknown tails, no or unknown characteristic scale)	Quite robust to Black Swans	Limits of Statistics extreme fragility to Black Swans

Source: Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable* (New York: Random House, 2007).

things we can do if we focus on antiknowledge, or what we do not know.[22]

BLACK SWAN THEORY: First Quadrant: Simple binary payoffs . . . forecasting is safe, life is easy, models work. . . . These situations are, unfortunately more common in laboratories and games than in real life. We rarely observe these payoffs in economic decision making. . . . Second Quadrant: Complex payoffs. . . statistical methods may work satisfactorily, though there are some risks. . . use of models may not be a panacea, owing to preasymptotics, lack of independence, and model error. There clearly are problems here. . . . Third Quadrant: Simple payoffs . . . there is little harm in being wrong, because the possibility of extreme events does not impact the payoffs. Don't worry too much about Black Swans. Fourth Quadrant: Complex payoffs . . . is where the problem resides, opportunities are present too. We need to avoid prediction of remote payoffs, though not necessarily ordinary ones. Payoffs from remote parts of the distribution are more difficult to predict than those from closer points. Using the wrong models to try to predict the unpredictable causes us to expose ourselves to even greater risk and to be less prepared for events we failed to predict. The goal is not to predict the future, but to offer observations about the possible rare events. "We can turn these Black Swans into Gray Swans, reducing their surprise effect."[23]

Technology Risk Assessment

Technology risk assessment advocates a precautionary approach. The precautionary approach argues that decision making requires a more active and dynamic analysis of reliability and risk mitigation management that emphasizes processes, particularly with regard to information flow and human error.[24]

In Table 10.4 we have four regions, but use different names. Rather than "ignorance" we use the more neutral term "unknowns." Rather than "fuzziness" as the category, we use "fuzzy logic" as the policy frame in the region or vagueness. "Ambiguity" refers to the overall terrain.

> For its part, a "precautionary" approach reflects a rather different perspective, introducing a wide range of emerging concerns in the risk governance debate. In the most general of terms, it contrasts with a reductive "risk-based" approach in extending attention to themes such as complexity, variability and nonlinear vulnerabilities in natural systems. A precautionary approach highlights the consequent potential for "surprise." It places greater emphasis on active and dynamic choices between technology and policy alternatives than do "risk-based" approaches.[25]

The fundamental difference between Black Swan Theory and the other approaches is that it launches from and is preoccupied with a negative framing of the issue—a critique of the approaches taken by analysts who are grounded in statistical models. Black Swan Theory sees the primary

Table 10.4 Framing the Terrain of Knowledge in Technology Risk Assessment

		Knowledge about Outcomes	
	Continuum of outcomes	**Set of Discrete outcomes**	**Poorly defined outcomes**
Knowledge about Likelihoods	RISK		FUZZINESS
	Apply:		Apply:
Firm basis for probabilities	frequentist distribution functions	discrete frequentist probabilities	fuzzy logic
Shaky basis for probabilities	Bayesian distribution functions	discrete Bayesian probabilities	
No basis for probabilities	UNCERTAINTY Apply: scenario analysis		IGNORANCE Apply: diversity

Sources: Andrew Stirling, *On Science and Precaution in the Management of Technological Risk*, European Science and Technology Observatory, 2001; Andrew Stirling, *On the Economics and Analysis of Diversity*, SPRU Paper No. 28, University of Sussex, 2000.

task as insulation against the harmful effects of negative black swans. In fact, Black Swan theory suggests that "while in the first three quadrants you can use the best model you can find, this is dangerous in the fourth quadrant: no model should be better than just any model."[26] However, it does not examine those models, in part because they have been highly developed in the fields that the theory is critiquing.

Technology Risk Assessment takes a positive approach, seeking to examine the methods used in the other quadrants and extract useful insights, without losing sight of the limitations of the methods in the face of unknowns (ignorance). The idea is to use the methods to explore each region to narrow the size of the unknowns. It may well be that ignorance is not the simple sum of risk, uncertainty, and vagueness, but it is also reasonable to use what we can learn from the analysis of risk, uncertainty, and vagueness to narrow the scope of ignorance, as long as we do not make the mistake of assuming that that is all there is to ignorance.

Technology Risk Assessment launches from a positive assessment of the value of diversity. The performance of a diverse system is superior because it fosters innovation, creativity, mobility, flexibility (anti-lock-in), pluralism, and a more rigorous selection process. Thus, diverse systems diminish the impact of black swans and are better equipped to exploit the opportunity of white swans.

Project and Risk Mitigation

Project and risk mitigation emphasize practical measures to gain knowledge and mitigate risk.

> The challenge in managing uncertainty, to whatever degree, is to find the balance between planning and learning. Planning provides discipline. . . . Projects in which variation and foreseen uncertainty dominate allow more planning, whereas projects with high levels of unforeseen uncertainty and chaos require greater emphasis on learning.[27]

Table 10.5 summarizes the project management literature. The most difficult circumstance is chaos, where variables and relationships are unknown. The challenge of decision making in distributed information systems reflects the challenge of building an intelligence-driven electricity system in the 21st century described in Chapter 9.

1. Variation—comes from many small influences and yields a range of values on a particular activity.

Table 10.5 Framing the Terrain of Knowledge: Project Management and Conditions of Extreme Ambiguity

		Uncertainty		
Ambiguity		Low	High	
	Low Variation	Model Using Variables known Values known Relationships known	Model Using Variables known Values unknown Relationships known	
High, Level 1	Foreseen Uncertainty	Model Building Variables known Values known Relationships unknown	Unforeseen Uncertainty	Model Building Variables known Values unknown Relationships unknown
High, Level 2			Chaos	Variables unknown Relationships unknown

Sources: Stephen Schrader, William M. Riggs, and Robert P. Smith, *Choice over Uncertainty and Ambiguity in Technical Problem Solving*. Alfred Sloan School of Management, Working Paper #3533-93-BPS, February 1993; Gene B. Alleman, *Five Easy Pieces of Risk Management*, May 8, 2005; Robert B. Duncan, "Characteristics of Organizational Environments and Perceived Environmental Uncertainty," *Administrative Science Quarterly* 17 (1972).

2. Foreseen Uncertainty—are uncertainties identifiable and understood influences that the team cannot be sure will occur. There needs to be a mitigation plan for these foreseen uncertainties.
3. Unforeseen Uncertainty—is uncertainty that can't be identified during project planning. When these occur, a new plan is needed.
4. Chaos—appears in the presence of "unknown unknowns."[28]

Uncertainty: Characteristic of a situation in which the problem solver considers the structure of the problem (including the set of relevant variables) as given, but is dissatisfied with his or her knowledge of the *value* of these variables. Ambiguity level 1: Characteristic of a situation in which the problem solver considers the set of potential relevant variables as given. The *relationships between the variables and the problem solving algorithm* are perceived as in need of determination. Ambiguity level 2: Characteristic of a situation in which the set of *relevant variables as well as their functional relationship and the problem solving algorithm* are seen in need of determination. In the case of uncertainty reduction, the key tasks are information gathering and integration. In the case of ambiguity reduction, the tasks are model building, negotiation, problem framing, evaluating and reframing, and model testing.[29]

UNCERTAINTY-AMBIGUITY MATRIX: Two dimensions of the environment are identified. The simple-complex dimension is defined as the number of factors taken into consideration in decision making. The static-dynamic dimension is viewed as the degree to which these factors in the decision unit's environment remain basically the same over time or are in a continual process of change. Results indicate that individuals in decision units with dynamic-complex environments experience the greatest amount of uncertainty in decision making. The data also indicate that the static-dynamic dimension of the environment is a more important contributor to uncertainty than the simple-complex dimension. . . . Managing "in the presence" of risk, variance and uncertainty is the key to success. . . . Although each uncertainty type is distinct, a single project may encounter some combination of four types:

In general, when work is distributed across space and time among multiple people, certain latent conditions necessarily exist that may lead to future mishaps. These include information sharing, coordination, communication, procedures, training, and knowledge capture and reuse. Information sharing may be absent, incomplete, incorrect, or not done in a timely manner. Coordination activities

> may be disorganized, untimely, missing, or unnecessarily difficult for a particular organizational structure. Poor communications practices, inappropriate initial framing of the interaction, poor training and poor procedure design may lead to poor information sharing and coordination, which may directly lead to mishaps. . . . Distributed work also requires distributed knowledge; therefore, poor knowledge capture and lack of reuse are issues as well.[30]

Other Views on Complex Ambiguity and Decision Making

As a description of the challenges of a hostile environment in which the terrain and presence of black swans is difficult to see, the expression "fog of war," interpreted to mean that "war is inherently volatile, uncertain, complex, and ambiguous,"[31] can be aptly applied to these efforts to map the terrain of knowledge. The advice offered to the military commanders when contemplating "cyberwar" is similar to the advice derived from the schools of thought cited in this chapter.

> We need to practice with the "radios turned off" and officers must become comfortable with uncertainty rather than keep grasping for more certainty. While we have the most robust communications, we also want to make sure we can operate with none of it. . . . Advantage on any battlefield—albeit episodic and ephemeral—will favor the commanders who best manage what they cannot master.[32]

Efforts to statistically model attacks in modern warfare end up in the "precaution" mode.[33] "This won't necessarily help a commander in the field deal with the day-to-day. . . . However, if the model predicts that a large attack is likely to happen soon, governments or military commanders could take steps to prevent its occurrence by more closely monitoring communications of enemy combatants. Officials may also potentially lessen the impact of an attack by moving civilians and soldiers away from likely targets."[34]

Resource acquisition in today's electricity sector may not be as daunting as war or space exploration, but it faces the "fog of the future," which at the start of the 21st century has certainly become much more "volatile, uncertain, complex, and ambiguous." We suggest that the analytic tools and policy instruments to describe the regions of knowledge can help decision makers to become comfortable with dramatically increased uncertainty and to be better able to manage what they have become much less able to master.

The literature on space exploration summarizes the challenges as follows:

> NASA space exploration should largely address a problem class in reliability and risk management stemming primarily from human error, system risk and multiobjective trade-off analysis by conducting research into system complexity, risk characterization and modeling, and system reasoning. In general, in every mission we can distinguish risk in three possible ways: a) known-known, b) known-unknown, and c) unknown-unknown. . . .
>
> Human reliability in systems cannot be verified with full coverage and components will fail or degrade, operators will make mistakes, and operating environments are uncertain. In addition, the state of the system and its environment may dynamically increase control complexity or decrease reaction times such that traditional control means are inadequate.[35]

While it can be argued that the condition of complex ambiguity has become greater as the global society becomes a highly interconnected, recursive system, the challenge of decision making in the face of the unknown has long been a fundamental part of the human condition. Analogies to Greek mythology and theology, summarized in the following text box, remind us of this.

CHARACTERIZATIONS OF THE KNOWLEDGE DILEMMA

Mythological risk classification

These risk types, named after metaphors from Greek mythology, are comprised by the following characterization of risks:

Damocles: high catastrophic potential, probabilities (widely) known
Cyclops: no reliable estimate for probabilities, high catastrophic potential
Pythia: causal connection confirmed, damage potential and probabilities unknown
Pandora: causal connection unclear, high persistency and ubiquity
Cassandra: intolerable risk of high probability and great damage, but long delay between causal stimulus and negative effect
Medusa: large potential for social mobilization without clear scientific evidence for serious harm

Damocles and Cyclops: risk-based. These risks can be handled and managed adequately by strategies and regulations based on the two main risk characteristics: extent of damage and probability of occurrence.

That is particularly so with the Damocles class, since here the probabilities are well known. With the Cyclops class, precautionary measures are more appropriate, since here the probabilities are not well defined.

Pythia and Pandora: precautionary. These risks are characterized by a high degree of uncertainty as to probability of occurrence and extent of damage, hence a "just in case" approach may be justified.

Cassandra and Medusa: discursive. These risks are characterized by either a delay effect, where the dangers initially may not be known or perhaps are even ignored, or risks where presumably harmless effects are perceived as threats by certain portions of the public or pressure groups. These risks require knowledge-building strategies to raise awareness and confidence.

Source: Andreas Blinke and Ortwin Renn, "Precautionary Principle and Discursive Strategies: Classifying and Managing Risks," *Journal of Risk Research*, 4, no. 2 (2001).

Theological

> In many religions, **Heaven** is a realm, either physical or transcendental in which people who have died continue to exist in an afterlife. Heaven is often described as the holiest place, accessible by people according to various standards of divinity, goodness, piety, faith or other virtues. . . . Many religions state that those who do not go to **heaven** will go to another place, hell, which is eternal in religions such as Christianity. Some religions believe that other afterlives exist in addition to heaven and hell, such as purgatory, though many hells, such as Naraka, serve as purgatories themselves. Some belief systems contain universalism, the belief that everyone will go to heaven eventually, no matter what they have done or believed on earth. Some forms of Christianity and other religions believe hell to be the termination of the soul.

In many religious traditions, **Hell** is a place of suffering and punishment in the afterlife. Religions with a linear divine history often depict Hell as endless. Typically these traditions locate Hell under the Earth's external surface and often include entrances to Hell from the land of the living. Other afterlife destinations include Heaven, Purgatory, Paradise, Naraka, and Limbo.

In the theology of the Catholic Church, **Limbo** (Latin *limbus*, edge or boundary, referring to the "edge" of Hell) is a speculative idea about the afterlife condition of those who die in original sin without being assigned to the Hell of the damned. Limbo is not an official doctrine of the Roman Catholic Church or any other. Medieval theologians described the underworld ("hell," "hades," "infernum") as divided into four distinct parts: hell of the damned (which some call Gehenna), Purgatory, limbo of the fathers, and limbo of infants. "Limbo of the Patriarchs" or "Limbo of the Fathers" (Latin *limbus patrum*) is seen as the temporary state of those who, in spite of the personal sins they may have committed, died in the friendship of God, but could not enter Heaven until redemption by Jesus Christ made it possible.

Purgatory is the condition or process of purification or temporary punishment in which, it is believed, the souls of those who die in a state of grace are made ready for Heaven.

There are parallels between the mythological and the theological. In classical Greek Mythology, the section of Hades known as the Fields of Asphodel were a realm much resembling Limbo, to which the vast majority of people who were held to have deserved neither the Elysian Fields (Heaven) nor Tartarus (Hell) were consigned for eternity. . . . In classic Greek mythology, below Heaven, Earth, and Pontus is Tartarus, or Tartaros (Greek Τάρταρος, deep place). It is either a deep, gloomy place, a pit or abyss used as a dungeon of torment and suffering that resides within Hades (the entire underworld) with Tartarus being the hellish component. In the Gorgias, Plato (c. 400 BC) wrote that souls were judged after death and those who received punishment were sent to Tartarus. As a place of punishment, it can be considered a hell. The classic Hades, on the other hand, is more similar to Old Testament Sheol. . . . The envisioning of Heaven, Hell, and Purgatory as places in the physical universe is not a Church doctrine. However, in antiquity and medieval times, Heaven and Hell were widely regarded as places existing within the physical universe: Heaven "above", in the sky; Hell "below", in or beneath the earth. Similarly, Purgatory has at times been thought of as a physical location.

Sources: http://en.wikipedia.org/wiki/Heaven; http://en.wikipedia.org/wiki/Hell; http://en.wikipedia.org/wiki/Limbo; http://en.wikipedia.org/wiki/Purgatory.

Ignorance is not bliss for decision makers in the land of the living; it is hell for decision makers. Decision makers are better off in Limbo than hell because in this space, characterized by vagueness, they can analyze contingencies and build in monitoring devices that adjust system performance. They are better off in purgatory than hell because, in this space characterized by uncertainty, they can analyze scenarios and buy real options delaying important decisions until the uncertainty is, hopefully, reduced. Unfortunately, there is no heaven on earth for decision makers dealing with electricity resource decisions; the best decision makers can hope for is to face risk, against which they can hedge.

REGIONS OF KNOWLEDGE AND NAVIAGATIONAL TOOLS

The regions of knowledge and the analytic approaches to navigate them can be briefly described as follows.

Risk: Hedging

In some circumstances the decision maker can clearly describe the outcomes and attach probabilities to them. Risk analysis allows the decision maker to hedge by creating a portfolio that balances more and less risky assets, particularly ones whose variations are uncorrelated. This risk analysis has it origin in the financial sector and was first articulated over half a century ago (portfolio theory).[36] The statistical methods that lie beneath risk-based probability analysis have been the primary targets of criticism in Black Swan Theory and Technology Risk Analysis because the underlying distribution of outcomes is frequently unpredictable.

In electricity resource acquisition, risk is generally used to refer to fuel price risk. In the short and mid-term, capital costs are fixed (rate-based). In the regulated context, fuel price adjustment clauses shift all the fuel price risk for fossil fuels onto the ratepayer. In the market context, the market clearing price is often set by the variable cost of gas-fired generation, which means price risk is recovered from consumers.[37] From the consumer/societal perspective, fuel price volatility should be taken into account. Portfolio theory was offered as the analytic approach to do so.

Vagueness: Fuzzy Logic

In some circumstances, decision makers may not be able to clearly identify the outcomes, but they know that the system will fluctuate. It would appear that the complexity of outcomes deserves at least as much attention as risk and uncertainty. Instead of just attempting to avoid areas of vagueness, the decision maker wants to take an approach that can monitor the condition of the system and adapt as it changes. An approach to this situation of vagueness, called "fuzzy logic," emerged from the computer science and engineering fields about a quarter of a century ago.[38]

We derive the approach to measuring vagueness by extending the logic of risk measurement to capital costs. In the short term, capital costs are known, but there is still a great deal of variability in these estimates due to vagueness in one of the main drivers of the cost of output, such as fuel costs. Moreover, as we move to the long term, capital costs become a source of vagueness because trends may drive costs up or down, and thus, outcomes are not known. With new technologies that have not been or are only beginning to be deployed, important processes such as learning-by-doing and economies of scale can lower capital costs significantly. To capture vagueness, instead of the variance of fuel prices we calculate the variance of total cost, including the full range of capital costs.

The vagueness surrounding capital costs for new low-carbon technologies affects both the amount of capital needed and the cost of capital.[39] Once the long-term variance in capital costs is entered into the analysis, it is also important to look at cost trends because some technologies are immature and are expected to undergo significant cost reductions as they are deployed. In the longer term, the goal for decarbonization shifts the focal point of attention from unabated natural gas to natural gas with carbon capture and storage.

Other areas of vagueness exist as well. The most common area of vagueness in electricity resource acquisition involves environmental impacts. There are fierce debates over, and shifting policy to address, a range of environmental issues (climate change, impacts of hydraulic fracking and nuclear waste); major black swans like accidents (nuclear melt downs, coal waste releases, mine explosions); and surprise findings (biomass emissions, methane leaks from pipelines). While some of these are typically included in the fuel-price scenarios, others are treated as separate, external costs. In fact, the debate is so intense over the existence, magnitude, and impact of some these factors that they can be properly located in the region of the unknowns.

Uncertainty: Real Option Analysis

In some circumstances, the decision maker can clearly describe the outcomes but cannot attach probabilities to them. Here the decision maker would like to keep options open by not deciding, if that is beneficial. If the decision maker cannot wait, then the path chosen should be flexible, so that it affords the opportunity to deal with whatever outcomes occur. Like portfolio theory, real option analysis also emerged from the financial sector, but more recently a little over a quarter of a century ago.[40]

Real option analysis asks whether the expected outcome can be improved by waiting for more information.

> Unlike traditional discounted cash-flow analysis, real option theory explicitly accounts for flexibility in the manner in which an asset is developed and operated, often leading to higher asset values, as well as different optimal capacity planning and operation decisions. For example, accounting for different plant construction lead times in the face of demand uncertainty can lead to significantly different optimal capacity planning strategies.[41]

A discussion of the real option approach to assessing the impact of the uncertainty surrounding climate change policy provides a more technical summary of this issue.

> The company has the opportunity to wait . . . before making the investment. This allows it to avoid the potential loss that might occur if conditions turn out worse than expected. . . . Waiting could lead to a greater return on investment. . . . It would be rational to invest [sooner] only if this value of waiting is overcome by the opportunity cost of waiting (i.e. the income forgone due to delaying the investment). In order to trigger immediate investment, the expected gross margin of the project would need to exceed some threshold level which makes the opportunity cost of waiting greater than the value of waiting. This threshold depends on the length of time before [the investment must be made], the size of the anticipated price shock and the discount rate. These thresholds are calculated using a cash-flow model in which climate change policy is represented using carbon price as a proxy.[42]

While these authors envision monetizing the wait/invest decision with a price on carbon and a discount rate, the qualitative nature of the issue should be underscored. For the purpose of the analysis of electricity resource selection, a critical question is when must a decision be made to acquire a more costly, risky or uncertain resource to ensure that the lights (computers) stay on? At the moment when the integrity of the system could be put in jeopardy by waiting, the value shifts in favor of action.

Real option calculations are project-specific, but by focusing on key factors that expose consumers and utilities to the ravages of uncertainty, real option analysis can provide general insight into the uncertainty. In conditions of uncertainty, the greater the ability to wait or change, the better. Several key characteristics of technology options affect the ability to wait or change: the construction period, the size of the facility and the capital costs that must be sunk into the project. In this analysis, we integrate the uncertainty analysis into the cost-risk analysis by developing separate estimates of the cost of resources that reflect the time value of being able to wait to make decisions.

An important benefit of the ability to wait that is associated with small size, shorter lead time technologies is the ability to "right size" the portfolio. Large, lumpy projects create excess capacity, particularly where improvements in energy efficiency are slowing demand growth. Analyses that assume equal amounts of capacity added at the same time ignore this important effect. Not only can cost be delayed, but under some assumptions about demand growth, they can be put off so long that, given discount rates, they are essentially foregone.

The Region of Unknowns: Robustness and Precaution

In the most challenging situation, knowledge of the nature of the outcomes and the probabilities is limited.[43] Even in this state of ignorance, decision makers have strategies to cope and policies that can insulate the system. Here the analyst looks inward to the characteristics of the system to identify those that are most important. The decision maker seeks to build systems that are robust, that is, ensure the critical internal functions are performed adequately to maintain system viability under the most trying of circumstances. This framework has been developing for about two decades in technology risk assessment and the energy sector. Multicriteria evaluations of outcomes that lead to strategies that buy insurance and diversify assets are recommended.

Decision makers should examine the preferred alternatives based on risk, vagueness, and uncertainty for evidence that surprises, black or white swans, could be lurking beyond the area where the analysis has shed light. They need to identify additional potential costs and benefits that flow from sources of risk, vagueness, or uncertainty that have not been included in the previous analysis. While the primary concern is black swans, decision makers should not miss the opportunity to exploit the benefits of white swans.

Sufficiency: Given the primary goal of ensuring an adequate supply, the sufficiency of the resources that are identified as preferable to meet the need for electricity should be considered as an independent question. Insufficiency is the most important black swan to consider. The uncertainty/real option component of the overall approach is intended to address this issue, but it deserves special attention. The objective of achieving a robust resource mix points toward diversity of resources as a primary goal, but diversity should not come at the expense of sufficiency. A properly defined concept of diversity takes this into account. Thus, insufficiency is a constraint on diversity. Sufficiency analysis also should recognize constraints on both the availability and management of resources.

Sequence: When analyzing sufficiency, time is of the essence. Long-term predictions are extremely ambiguous. Flexibility requires that options are kept open as long as possible. The decision-making time frame for incremental decisions should be only as long as the longest lead time of the options being considered. If there are preferable options with shorter lead times, then they should be chosen, since there will be adequate time to bring the inferior option online later, if or when the preferable options are exhausted.

Unintended consequences: These outcomes are important to consider. For example, increasing the reliance on variable renewables can create grid management challenges where the grid was built to handle "traditional" generation. At current, relatively low levels of variable renewable penetration, this is not a major problem, but as their use increases a new approach to grid management will be appropriate. As we have seen, we have already entered a period of rapid expansion of these resources, so the time to begin the institutional transformation is now.

Consistency: One obvious type of black swan to look for is inconsistencies in recommendations from the other three regions. These would indicate an important area for analysis in the unknown region. This is a critical factor in the incompatibility between the central station nuclear approach and the renewable/distributed/demand-based approach.

Externalities: Other swans are positive and negative externalities. Environmental impacts, water consumption and security of supply are all important externalities. Efficiency, wind, solar are attractive options from the point of view of water consumption. Domestic resources are attractive from the point of view of supply security. Renewables and efficiency that displace natural gas can have large, positive consumption externalities. By lowering the demand for fossil fuels, they lower the price of fossil fuels and free supplies for other, high-value uses. Macroeconomic effects are also important: holding costs down and utilizing domestic resources tends to increase disposable income and increase economic activity.

11

APPLICATION OF MULTICRITERIA PORTFOLIO ANALYSIS

PRINCIPLES FOR NAVIGATING THE TERRAIN OF KNOWLEDGE

Awerbuch and Berger,[1] commenting on the work of Stirling, noted the tension between the assumptions underlying the four different approaches to decision making in the face of ambiguity.

> Andrew C. Stirling rejected the applicability of mean-variance portfolio theory on the grounds that fuel price movements have no pattern. He argued that "Decisions in the complex and rapidly changing environment of electricity supply are unique, major and effectively irreversible. . . ."
>
> Differentiating three basic states of incertitude . . . Stirling states that ignorance rather than risk or uncertainty dominates real electricity investment decisions. He conceptualizes diversification as a response to ignorance.
>
> Portfolio risk, however, is properly defined as total risk (the sum of random and systematic fluctuations) measured as the standard deviation of periodic historic returns.
>
> This is not to say, however, that certain fundamental changes in the future, such as significant market restructuring or radically new technologies, could not create 'surprises' by altering observed historic risk patterns. Such radical, discontinuous change is generally unpredictable. However, rather than letting such probabilities drive our decision approach, we find it more plausible to assume that the totality of random events . . . cover the reasonable range of expectations for the future.[2]

We do not believe the tension between the approaches poses a serious problem. The strategy that we advocate is for decision makers to intensively explore the risk, uncertainty, and vagueness regions, thereby, hopefully, shrinking the region of the unknowns. When the first three regions have been explored, the analyst should consider what else is still unknown and what needs to be done about it. This is consistent with the observation offered by Black Swan Theory and underscores an important point—knowledge and action go hand in hand in these schools of thought.

> A map is a useful thing because you know where you are safe and where your knowledge is questionable. So I drew . . . a tableau showing the boundaries where statistics work well and where it is questionable. Now once you identify where the danger zone is, where your knowledge is no longer valid, you can easily make some policy rules.[3]

Table 11.1 provides details on the policy prescriptions identified in Table 10.2. Perhaps the strongest reason to conclude that the schools of thought are not in conflict and provide a basis for a single broad framework is the strong similarity in the recommendations for action that they provide. Technology Risk Assessment and Black Swan Theory both draw heavily on biological and ecological sciences for their recommendations. Both analogize and emphasize the importance of insurance and look to natural forms, such as redundancy, flexibility and adaptability. Broad policy principles can be extracted from these approaches.

Unlike financial markets, where assets are generally highly liquid, technology resources in the electricity sector tend to be lumpy and illiquid. Where there are substantial differences in the size and lifespan of assets, as well as the time it takes to acquire them, additional advice can be derived from theories of decision making in complex, ambiguous situations. Table 11.2 underscore the fact that sequence is important.

- Identify the trade-offs between cost and risk and hedge to lower risk.
- Reduce exposure to uncertainty by buying time.
- Keep options open by acquiring small assets that can be added quickly. Fail small and early.
- Minimize surprises by avoiding assets that have unknown or uncontrollable effects.
- Create systems that monitor conditions and can adapt to change to maintain

The recognition that decarbonization should be seen as an undertaking whose primary challenge is to overcome inertia and market barriers and

Table 11.1 Defining Policy Rules For the Regions of Knowledge

Technology Risk Analysis	Black Swan Theory	Project & Risk Mitigation
Knowing your ignorance is the best part of knowledge. Precaution: Specific methods, techniques, instruments or measures which implement an approach which directly addresses the problems of multidimensionality, incommensurability, and ignorance. (a: 40) **Diversity:** diversity remains effective (at least in part) *even if the source or modalities of the prospective disruptions are effectively unknown*. By maintaining an evenly balanced variety of mutually disparate options, we may hope to resist impacts on any subset of these, even if we do not know in advance what these impacts might be. parallel series of different strategies Diversity => the inclusion of options which appear to perform less well as an insurance against changes in performance in other options (a: 27) **Variety**: e.g., the number of functionally redundant—but morphologically or operationally distinct—options sustained in parallel (b: 39)	The Black Swan attempts to provide a map of where we get hurt by what we don't know, to set systematic limits to the fragility of knowledge and to provide exact locations where these maps no longer work (347). The most obvious way to exit the Fourth Quadrant is by "truncating," cutting certain exposures by purchasing insurance, when available (370); one can buy insurance, or construct it to "robustify" a portfolio (371) **Redundancy** equals insurance and the apparent inefficiencies are with the cost of maintaining these spare parts and the energy needed associated—to keep them around in spite of their idleness; exact opposite of redundancy is naïve optimization (312) **Numerical, functional, adaptive:** The availability of spare parts, where the same function can be performed by identical elements, very often the same function can be performed by two different structures. When an organ can be employed to perform a certain function that is not its current central one (316–317). Species density: Based on the nonlinearity in damage, spread the damage . . . larger environments are more scalable allowing the biggest to get even bigger, at the expense of the	Development of critical technologies that **provide system resiliency will enable future systems to adapt and recover from these unanticipated problems.** Current technologies are not optimal for carrying out effective risk mitigation as they lack significant capability to assess system condition or to validate system performance. **System robustness, redundancy, and capability for rapid recovery are currently inadequate.** NASA space exploration should largely address a problem class in reliability and risk management stemming primarily from human errors, system risk, and multi-objective trade-off analysis, by conducting research into system complexity, risk characterization and modeling, and system reasoning. . . . Development activity will have to support **risk analysis, design**

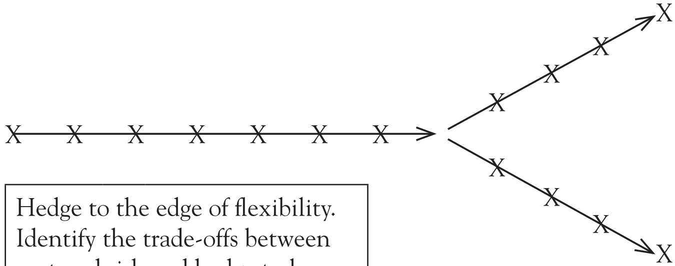
(*Continued*)

Table 11.1 (Continued)

Technology Risk Analysis	Black Swan Theory	Project & Risk Mitigation
Balance: the pattern in the apportionment across the relevant categories of the options (b: 39) **Disparity**: the nature and degree to which the categories themselves are different from each other (b: 40) **Flexibility** **Capacity to retain** as many options for as long as possible in advance of commitment, and **Ability to withdraw** (when commitment is made) without great penalty if prohibitive conditions arise (a: 27) **Resilience:** capacity to sustain performance under external perturbation (b: 2) **Robustness**: The capacity to sustain performance under extreme perturbation maintaining an established internal structure **Adaptability:** The capacity to sustain performance under external perturbation by changing internal structures (a: 27)	smallest.. . . . . . the successful killer will spread vastly more effectively (317). **Avoid over-specialization, promote optionality** The organism with the largest number of secondary uses is the one that will gain the most from environmental randomness and epistemic opacity (318). Optionality—since you have the option of taking the freebie from randomness (319). Compensate complexity with simplicity (375) **Robust to error:** Nothing should ever become too big to fail. What is fragile should break early, while it is small (374). Big is ugly & fragile: Mother Nature does not limit the interactions between entities; it just limits the size of the units (314) **Confine mistakes** The idea is simply to let human mistakes and miscalculations remain confined and to prevent their spreading through the system (322) **Durability:** Things that have worked for a long time are preferable (371). No Socialization of losses and privatization of gains (374). No incentives without disincentives (375)	**robustness, failure modeling, and system trade-offs** through the entire lifecycle of the enterprise, with **particular emphasis on early-phase capabilities.** Development of *tools for identifying, assessing, and trading risks* before and during formulation. Development *of safety and risk-related systems analysis tools* combines two thrusts, **addressing a) how risk profiles can be maintained and utilized through the fully lifecycle**, and b) **how system evolution affects designs.** Development of methods and tools that constitute a human learning "feedback" loop. Their goal is to improve *our understanding of the factors that contribute to aerospace accidents* and to develop ways to use that experience to improve designs.

Sources: Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable* (New York: Random House, 2010), 365; Andrew Stirling, *On Science and Precaution in the Management of Technological Risk*, European Science and Technology Observatory, 2001, 17: *On the Economics and Analysis of Diversity*, Science Policy Research Unit, University of Sussex, 2000, Chapter 2; "Risk, Precaution and Science; Toward a More Constructive Policy Debate," *EMBO Reports* 8 (2007); David A. Maluf, Yuri O. Gawdisk, and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety*, NASA Technical Reports, 2005.

Table 11.2 Sequencing Decisions Based on the Map of the Terrain of Knowledge

Region of Knowledge	Decision-Making Advice
Risk	 Hedge to the edge of flexibility. Identify the trade-offs between cost and risk and hedge to lower risk by acquiring assets that are uncorrelated.
Real Options	Choose sequence of hedges to preserve options. Reduce exposure to uncertainty by buying time. Keep options open by acquiring small assets that can be added quickly. Fail small and early.
Vagueness	Avoid long-term paths that are least controllable value. Minimize surprises by avoiding assets that have unknown or uncontrollable effects. Create systems that monitor conditions and can adapt to change to maintain system performance.
The Unknown	Buy insurance where possible, recognizing that diversity is the best insurance against the unknown. Build resilience with diversified assets by increasing variety, balance and disparity of assets. Value diversity; prefer options that support multiple assets and add to system robustness.

Source: Author.

correct pre-existing market imperfections, requires a broad consideration of policies (beyond simple price). The analysis of the terrain of knowledge can inform the selection of policies, just as it informs the selection of policies, just as it informs the selection of resources, as shown in Table 11.3.

Hedging against risk is the obvious cornerstone of portfolio building, but it turns out that risk is the easiest region of the terrain of knowledge to navigate. Real option analysis, responding to uncertainty, informs the decision maker about which hedges to buy first. Assessment of vagueness can identify pathways, longer-term sequences of technology choices, to

Table 11.3 Market Imperfections in the Regions of Knowledge and Policy Responses

VAGUENESS	RISK
Barriers: Public Goods learning-by doing, lack of economies of scale result in high capital cost and interest rate	**Barriers:** Perverse incentives, agency problems caused by misallocation of fuel price risk
Policy Responses: Incent learning, capture economies of scale and network effects with obligations, loan guarantees	**Policy Responses:** Reflect merit in dispatch, compensate low risk resources with a feed-in tariff
UNKNOWNS	**UNCERTAINTY**
Barriers: Black Swan: Network Management White Swan: GDP multiplier and consumption externalities	**Barriers:** Faulty calculation causes loss of real option value by choice of long lead time, high sunk cost projects
Policy Response: Promote diversity with funding of R&D, education, infrastructure funding	**Policy Responses:** Reward flexibility with capacity adders, facilitate consenting

Source: Author.

pursue. The general advice in the region of the unknowns to pursue diversity as a source of robustness is reinforced by the general observation that assets that can be shared, support multiple technologies, or contribute to system robustness are particularly attractive.

The set of policies in the risk region requires the market structural issues to be resolved so that renewables can overcome inertia and entrenched interests to compete on a level playing field in terms of incentives. Policies like obligations, merit order dispatch, and feed-in tariffs deliver immediate rewards to alternatives.[4] These compensate for the misallocation of risk that fails to take pricing volatility into account.

The set of policies in the vagueness region requires efforts to direct investment toward the newer resources. All low-carbon resources suffer from high capital costs and high hurdle rates of return because of their newness state. The state is ideally suited to absorb these risks because it can take a broader, long term view of social returns and trigger a potential for reduction of capital costs through learning and economies of scale.[5]

The set of policies in the uncertainty region aims to reduce the time it takes to bring projects on line. Rewarding flexibility with capacity adders, facilitate consenting, obligations to purchase alternatives are obvious possibilities.

The set of policies in the region of the unknowns involves research and development, with a focus on relieving the network management constraint so that the technological and economic limits of variable renewables are more clearly defined. Exploring the technologies that can expand the contribution of variable renewables in the longer term—interconnection, smarter grid and appliance technologies—also creates a more efficient electricity sector generally and one that will be able to more readily accommodate more uses, like the electrification of transportation, and one that is less susceptible to volatile swings in price.[6]

- Spreading the renewable resource base across geographic regions and resources creates a less variable pattern of generation.
- Storage capacity enhances the value of all variable resources and reduces the volatility of input prices.[7]
- Smarter networks increase the ability to balance generation and load.
- Smart grid development creates export markets for surpluses and more efficient import markets to meet deficits.

Figure 11.1 presents these policies across time by arraying them along a traditional diffusion curve approach for energy efficiency. The sequence is

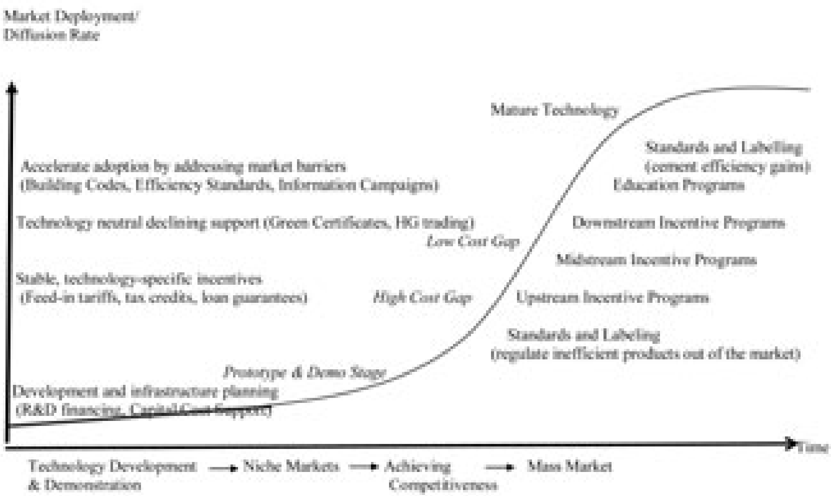


Figure 11.1 Tailoring Support to Meet Needs Along the Innovation Chain: Impact of Interventions on Highly-Efficient (HE) Technology Diffusion Rate

Sources: Entries above the curve: International Energy Agency, *Energy Technology Perspective, 2014: Harnessing Electricity's Potential* (Paris: International Energy Agency, 2014), 55. Entries below the curve: Stephane de la Rue du Can et al., "Design of Incentive Programs for Accelerating Penetration of Energy-Efficient Appliances," *Energy Policy* 72 (2014), 59.

similar to that identified based on the analysis of the terrain of knowledge. Standards are used across the lifecycle, first to eliminate inefficient products, later to cement efficiency gains.

MULTICRITERIA PORTFOLIO ANALYSIS

Awerbuch's response to Stirling and Taleb's description of the value of drawing a "tableau" provide the context for an empirical analysis using a multicriteria portfolio approach. Risk analysis is a tool for mapping the terrain of decision making that is embedded in a much larger framework. It is the beginning of the analysis, not the end.

The Portfolio Approach

Following Awerbuch, my framing of the empirical approach to developing navigation tools is based on financial market theory, which provides a framework for evaluating the trade-off between performance and risk. Figure 11.2 presents the basic approach, as a publication from the National Regulatory Research Institute attempted to introduce it to regulators.[8] Investors want to be on the efficient frontier, where risk and reward are balanced. They can improve their expected returns if they can increase their reward without increasing their risk, or they can lower their risk without reducing their reward. In the financial literature, risk is measured

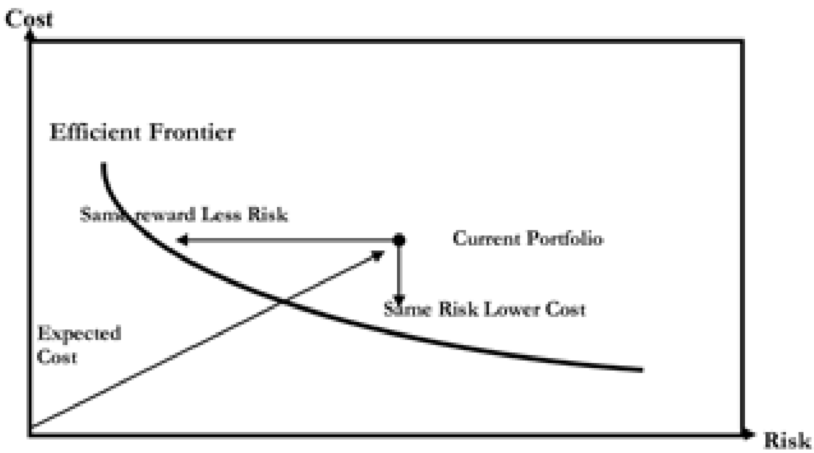


Figure 11.2 The Basic Approach to Portfolio Analysis

Sources: Based on Ken Costello, *Making the Most of Alternative Generation Technologies: A Perspective on Fuel Diversity* (NRRI, March 2005), p. 12; J. C. Jansen, L. W. M. Beurskens, and X. van Tilburg, "Application of Portfolio Analysis to the Dutch Generating Mix," *ECN*, February, 2006.

by the standard deviation of the reward. In applying this framework to the evaluation of generation options, analysts frequently measure reward as kilowatts per dollar (a measure of economic efficiency). This is the inverse of cost. Indeed, they use efficiency and cost interchangeably.[9]

Options that would move the portfolio toward the efficient frontier should be adopted since they embody lower cost and/or risk.[10] Much of the literature on portfolio and real option management as applied to the electricity sector focuses on identifying the optimal long-term mix of resources. Because so many factors are so variable over the long term, these analyses become a complex array of assumptions and alternative scenarios that then must hypothesize constraints or state preferences in order to sort out the wide range of possible outcomes. The results are complex. Even though the patterns are instructive, the cost in terms of complexity and transparency is significant.

An alternative approach that can be found in the literature is to use these tools to deal with more incremental decisions. The map of the terrain of decision making indicates which alternatives are preferable on an individual basis. In other words, rather than worry about the optimal end point, we can focus on the relative position of the individual technologies in the decision space and ask whether including the asset in the portfolio would be moving in the right direction. This approach was offered in direct response to a desire for more incremental and transparent applications of the theory.[11] Movement toward the origin is considered positive. Movement along the risk-cost frontier is neutral. Movement away from the origin is less desirable.

To assess the attractiveness of the portfolios, we calculate the weighted average cost of the assets included in the portfolio and the weighted average standard deviation of the portfolio. The key to the analysis is the correlation between variation in the cost of each of the assets.

The formula is

$$\sigma^2_{AB} = {}_{AB}\sqrt{w^2_A{*}\sigma^2(C_A) + w^2_B{*}\sigma^2(C_B) + 2{*}(w_A){*}(w_B){*}Cov(C_A, C_B)}$$

Where:

σ_i^2 **=** standard deviation of the i resource
w_i = weight of the i resource
C_i = cost of the i resource
Cov = Correlation of the Resources

Since our goal is to locate the current, familiar approaches to analysis of resources in a more systematic and transparent framework for decision

Table 11.4 Comparison of Assumptions, Data, and Analytic Approaches

Analytic Approaches	Traditional Approach	Multicriteria Portfolio Analysis
Reference Point	Natural gas CCT cost without carbon capture is the base case.	Efficient frontiers for both gas and coal are identified.
		Optimum portfolios identified
		Wind used as referent for qualitative analysis
Cost	Levelized	Same
Capital Cost	Range of capital costs	Fossil fuel capital cost adjusted for risk
Risk	Average with range, time is the x-axis	Variability = standard deviation of costs used as the X-axis, distance as expected value
Uncertainty	Range of estimates and scenarios	Price adjusted by lost use of money Variability adjusted by possibility of abandonment
Vagueness	Hi-Lo capital cost; Hi-lo discount rate	All cases average and variation in capital; operating costs included in the x-axis adjusted risk/uncertainty and the y-axis adjusted for vagueness

Source: Author.

making, Table 11.4 summarizes the difference between the traditional approach and multicriteria portfolio analysis.

In the empirical analysis below, we use the array of resources in this space to map two key features of the terrain of decision making. First, we use the array of resources to calculate a measure of attractiveness. The distance of a resource from the origin measures the risk-cost characteristics of the resource (giving risk and cost equal weight). Resources that are farther from the origin (measured as the Euclidean distance) are less attractive. We then assess the expected cost for the portfolios that were subject to the merit order analysis in Chapter 6.

THE KEY DRIVERS OF COST AND AMBIGUITY IN THE MID-TERM

In Figure 11.3, we apply this approach to the economic data analyzed above. We use every cost estimate offered in the three data sets we have

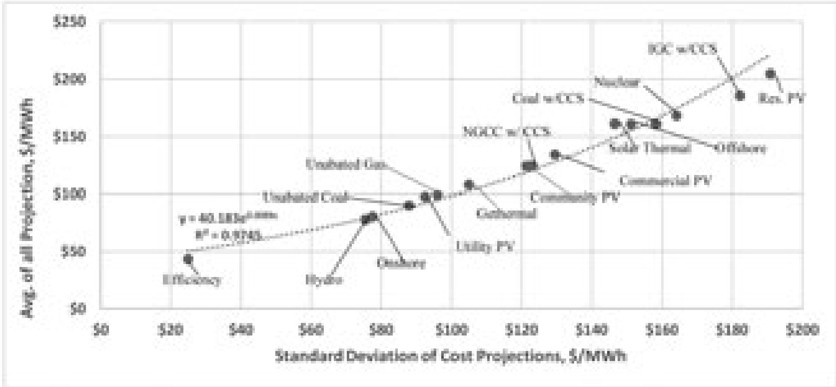


Figure 11.3 Expected Costs Based on All Projections

analyzed—Lazard, Jacobson et al., and Australia—to calculate the average cost estimate and the standard deviation. This mixes short- and longer-term price projections, which we think is appropriate, since short-term projections with less uncertainty should influence the selection of assets. Using total costs, which includes capital, fuel and operating costs to define variation in price projections, rather than only fuel costs, is also appropriate for a long term analysis. Figure 11.3 presents the array of expected costs. The rank order and magnitude of the projection, which determines the order in which assets would be added to the portfolio is virtually identical to the conclusions from the "merit order" analysis presented above.

We can also test that conclusion with formal portfolio analysis, although we will keep it simple here. The merit order analysis has considered a series of portfolios. Business as usual as the base, the 100 percent low carbon, low pollution portfolio, and low carbon, high pollution portfolios. Fossil fuel costs tend to be positively correlated (assumed here r = .4). One would not want to include both coal and gas, if they can be avoided. This raises the standard deviation and expected cost of the BAU portfolio. Nuclear and hydro would tend to have no inherent correlation, although hydro, which is more flexible, could be easier to manage to have a negative correlation with other resources (although here it is assumed that r = 0). The correlation between wind and solar will vary from location-to-location, but they tend to be slightly negatively correlated (assumed here r = −.2). We use the proportions of assets (generation choices) from Jacobson for low carbon/low pollution and the business as usual. For the low carbon/high pollution we use the proportions from the Deep Decarbonization study.

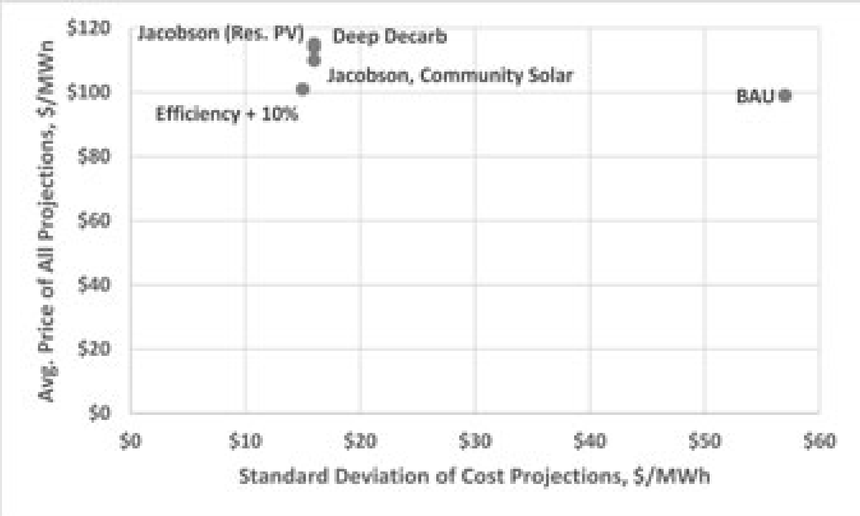


Figure 11.4 Expected Cost of Major Low Carbon Portfolios: Resource Costs Only

Figure 11.4 shows that the results of the portfolio analysis are similar to the merit order analysis. The business as usual scenario has a slightly higher cost than several of the low carbon scenarios. Community solar as the "marginal" asset is preferable to residential PV. Efficiency is clearly superior. Inclusion of nuclear increases the cost putting the portfolio at the level of BAU and just below the portfolio that includes residential PV.

Including the price of carbon or pricing pollution into the analysis would reinforce the conclusion. The BAU portfolio would become much more costly. To the extent that carbon capture is not 100 percent, a price on carbon would raise the cost of any portfolio that included those technologies. The energy intensive nature of nuclear construction, uranium mining, and decommissioning, also puts nuclear at a slight disadvantage with respect to a cost of carbon.

Figure 11.5 adds the cost of noncarbon pollutants from Figure 5.2 to the cost of each resource. To the extent that the uncertainty around the cost of each pollutant might vary and the resources emit different pollutants, one would want to adjust the estimated standard deviations. Here we assume that the uncertainty around noncarbon pollutants affects only the price. Figure 11.5 plots the expected costs for the individual resources and shows the values for the major portfolios. Since the renewables pollute less, the advantage of the 100 percent renewable portfolio increases. Putting a price on carbon would move the results farther in the same direction, as shown by the arrows.

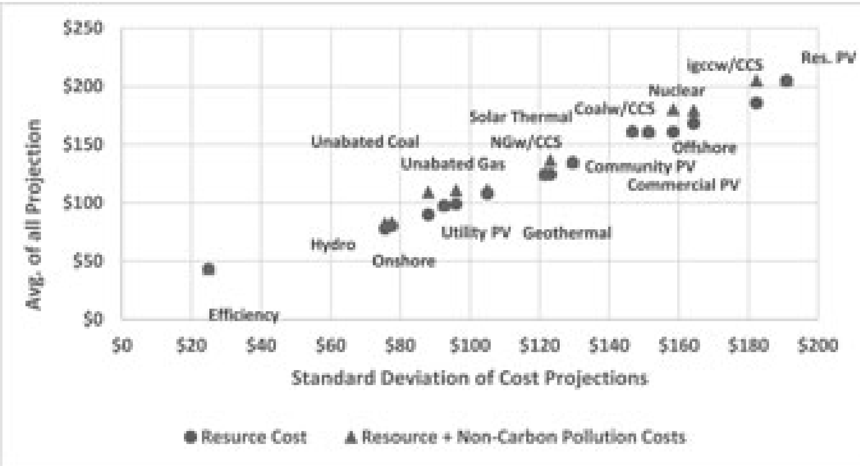


Figure 11.5 Expected Cost of Resources and Major Portfolios: Resource Plus Noncarbon Pollution Costs

COMPARISONS WITH OTHER APPROACHES

Portfolio Analysis as an Overall Approach

Watkiss et al. have reviewed the literature on "the use of new economic decision support tools for adaptation assessment"[12] that identifies many of the tools we have described and applied. We have grounded our approach in the deep intellectual origins across disciplines, organized them according to the specific sources of ambiguity they address and derived specific policy principles for each region of knowledge.

As shown in Table 11.5, we treat the portfolio methodology as an overarching approach to all four regions of knowledge. Watkiss et al. list portfolio analysis as a tool, equivalent to the others. We treat it as the overarching analytic methodology that can be used to implement each of the other tools. We have gone beyond description to organize the tools according to a comprehensive definition of the terrain of decision making, which enables us to locate each of the tools in one of the four regions of knowledge. We have offered a more detailed and comprehensive description of the regions of knowledge, that links the conditions in the decision space to methods for exploring it and provides a justification for the specific evaluation tools. Moreover, we provide a guide to the sequence and interrelationship of the tools.

Within the regions, our risk analysis is close to their cost-benefit analysis. Chapters 6 and 7 were implicitly cost-benefit analyses that compared costs, while varying nonquantitative benefit assumptions about carbon and

Table 11.5 Ambiguity Defined by Four Regions of Knowledge

	High	Vagueness: Fuzzy logic Economic decision making under uncertainty Iterative risk management	Risk: Hedging Economic decision making under uncertainty Robust decision making
Knowledge of probabilities of outcomes			
	Low	Unknown: Robustness Traditional economic decision support Cost benefit analysis Cost effectiveness analysis	Uncertainty: Real Option Economic Decision making under uncertainty Real Option Analysis
		Low	High
		Knowledge of nature of outcomes	

Multi-criteria Portfolio Analysis View of Decision Support Tools

Overarching Approach: Portfolio Analysis: Analyzing combinations of options, including potential for project and strategy formulation.

Risk: Hedging: Cost-Benefit/Effectiveness Analysis Short-term assessment, for market and non-market sectors. Particularly relevant where clear headline indicator and dominant impact (less applicable cross sectoral and complex risks). Most useful when: Climate risk probabilities known, Climate sensitivity small compared to total costs/benefits, Good data exists for major cost/benefit components.

Vagueness: Fuzzy Logic: Frameworks for Uncertainty—Iterative Risk Assessment Project level. Strategy level for framework for planning. Most useful when: Clear risk thresholds, Mix of quantitative and qualitative information, For non-monetary areas (e.g. ecosystems, health).

Uncertainty: Real Options: Real Options Analysis Project based analysis. Large irreversible capital investment, particularly where existing adaptation deficit. Comparing flexible vs. nonflexible options. Most useful when: Large irreversible capital decisions, Climate risk probabilities known or good Information, Good quality data exists for major cost/benefit components.

Unknowns: Robustness and Precaution: Robust Decision Making: Project and strategy analysis. Conditions of high uncertainty, Near-term investment with long life times (e.g. infrastructure).

Source: Author; Paul Watkiss et al., "The Use of New Economic Decision Support Tools for Adaptation Assessment: A Review of Methods and Applications, Towards Guidance on Applicability," *Climatic Change* 132 (2015).

pollution. We characterize vagueness as an "iterative risk assessment," and real option analysis as uncertainty. In our framework, the region of the unknown is close to their robust decision making.

Our recommendations for the approach to analysis and adoption of policies apply principles that are similar to theirs. We start from and drive the overall analysis form the first principle that these tools are suitable for different types of adaptation problems. We attach great significance to their second observations that "there are differences in the relevant time periods." The key principle of "fail small and early," reflects the attention to scale. Finally, we agree wholeheartedly that "they are not mutually exclusive."

While most efforts to incorporate ambiguity into the selection of resources take this qualitative ranking approach, a recent effort by Watkiss et al. takes a broader approach that claims it "provides a critical review and assessment of existing economic decision support tools (cost-benefit analysis and cost-effectiveness analysis) an uncertainty framework (iterative risk management) and alternative tools that more fully incorporate uncertainty (real options analysis, robust decision making and portfolio analysis)." As shown in Table 11.5, the tools they identify are similar to the tools we have described in this section. Watkiss et al. argue that "these tools are suitable for different types of adaptation problems" and note that the tools are "not mutually exclusive." The distinguishing features are similar to the ones introduced in our discussion—the type of problem (whether outcomes can be represented quantitatively or are qualitative and whether probabilities can be calculated), the time period and the scale. Their analysis provides an opportunity to describe how we have tried to advance the acceptance of a new decision paradigm.

We have gone beyond description to organize the tools according to a comprehensive definition of the terrain of decision making, which enables us to locate each of the tools in one of the four regions of knowledge. We have offered a more detailed and comprehensive description of the regions of knowledge, that links the conditions in the decision space to methods for exploring it and provides a justification for the specific evaluation tools. Moreover, we provide a guide to the sequence and interrelationship of the tools.

Portfolio Analysis of Resource Selection

While Watkiss, et al. discuss the general modeling of risk and the use of portfolio analysis, their examples tend to come from broad environmental studies, not resource selection in the energy or electricity sector. The use of portfolio analysis has been growing for some time. It was first applied in an effort to convince policy makers to take variable cost uncertainty into account, thereby recognizing that assets that did not rely on fossil fuels would lower expected costs. Some of the early analyses also presented full optimization studies, which were very complex.

More recently, efforts to model resource selection at a middle level have expanded. An interesting example is a recent study by Jason Rauch that uses this approach to identify the optimal portfolio for generation resources in New England and corroborates my findings with detailed regional data.[13] The purpose of his paper is to show that taking risk into account is important to arrive at optimal decisions and to demonstrate a rigorous methodology that can be easily implemented by public utility commissions. Here we move beyond that laudable goal and draw policy conclusions that address big questions in the ongoing debate about low-carbon resource acquisition: How much nuclear belongs in the portfolio? How does carbon regulation affect the attractiveness of the alternatives? How much gas is needed? How large are the cost increases?

The makeup of the optimal portfolio provides clear answers to these questions, which parallel much of our analysis.

- Nuclear is not included in any optimal portfolio.
- Gas is 15–16 percent of the optimal portfolio.
- Wind accounts for 34–48 percent, depending on the cost of integration.
- Hydro is in the range of 21–34 percent (hydro is up when wind is down).
- If the decision maker ignores both risk and carbon mitigation, the preferred portfolio is 96 percent gas, but if the decision maker considers either *risk or carbon mitigation*, the gas share is reduced by five-sixths.

Carbon regulation has little impact on the mix of generation in the optimal risk-adjusted price portfolio.

- The optimum resource mix is roughly the same in both the base case and the zero carbon case.
- However, once one moves to decarbonize the electricity sector, optimal portfolio analysis becomes particularly important.
- An approach to zero carbon emissions that is risk aware decreases the expected cost by just under 20 percent.
- An optimal portfolio strategy keeps the cost increase under 13 percent.

- Controlling the cost of integrating large shares of wind is important, as it can add 2 to 4 percent to the cost of the optimal portfolio.

Combined, these observations give a clear conclusion for policy makers. A well-designed transition to low-carbon resources that controls the cost of integrating renewables and is optimized for price and risk can cut cost increases by 40 to 50 percent. Spread across a decade and a half, as in the EPA Clean Power Rule, the impact would be less than 1 percent per year, in line with the EPA's estimates. Nuclear power is not needed to achieve these results.

Technology Evaluations

Awerbuch and Yang[14] offer a qualitative comparison of generic features of generating technologies and provide "a qualitative assessment of how the various types of risk in liberalized electricity markets affect the three main base load generation technologies" alongside five alternative generation technologies (see Table 11.6).

Our analysis in this Chapter has attempted to capture and quantify the first six features as they affect cost, risk, uncertainty, and vagueness surrounding these technologies. The seventh feature in the table—regulatory risk—is treated as a target policy variable in our analysis, not a feature of the generation technologies. Wind and solar are clearly among the most attractive options; nuclear is the least. The upper graph in Figure 11.6 compares the Awerbuch/Yang analysis to our multicriteria results. We convert the qualitative evaluations into five point scales, from very low to very high, and sum across the six characteristics. We compare this to the expected cost based on total resource costs with price trends. These expected costs are based solely on economic costs.

The middle graph in Figure 11.6 shows the correlation between a recently published effort by Binz et al. to evaluate the risk of alternative with a 100-point qualitative scale and the portfolio-based estimate of the expected cost. The lower graph in Figure 11.6 shows the correlations between the average or the experts and our multicriteria analysis and the expert evaluations.

The multicriteria portfolio analysis shows strong correlations with the qualitative approaches. Efficiency, wind and solar are quite attractive. Nuclear is quite unattractive and the other resources are grouped tightly together. The approaches yield the same ranking and the correlation is strong.

Table 11.6 Qualitative Comparison of Generic Features of Generation Technologies Operationalized in the Multicriteria Portfolio Analysis

	Region of Knowledge and Sources of Ambiguity						
	Risk			**Uncertainty**		**Vagueness**	**Regulatory Risk**
Generic Features	Fuel Prices	CO_2 Emissions	Operating Costs	Unit Size	Lead Time	Capital Cost (Quantity & ROI)	
Technologies							
CCGT	High	Medium	Low	Medium	Short	Low	Low
Coal	Medium	High	Medium	Large	Long	High	High
Nuclear	Low	Nil	Medium	Very Large	Long	High	High
Wind	Nil	Nil	Very Low	Small	Short	High	Medium
Hydro	Nil	Nil	Very Low	Large	Long	Very High	High
Reciprocating Engine	High	Medium	Low	Small	Very Short	Low	Medium
Fuel Cells	High	Medium	Medium	Small	Very Short	Very High	Low
Photovoltaics	Nil	Nil	Very Low	Very Small	Very Short	Very High	Low

Source: Shimon Awerbuch and Spencer Yang, "Using Portfolio Theory to Value Power Generation Investments," in *Analytic Methods for Energy Diversity and Security*, ed. Morgan Bazilian and Fabien Rocques (Oxford, U.K.: Elsevier, 2008), 63, citing International Energy Agency/Nuclear Energy Agency, *Projected Costs of Generating Electricity: 2005 Edition* (Paris: OECD, 2005).

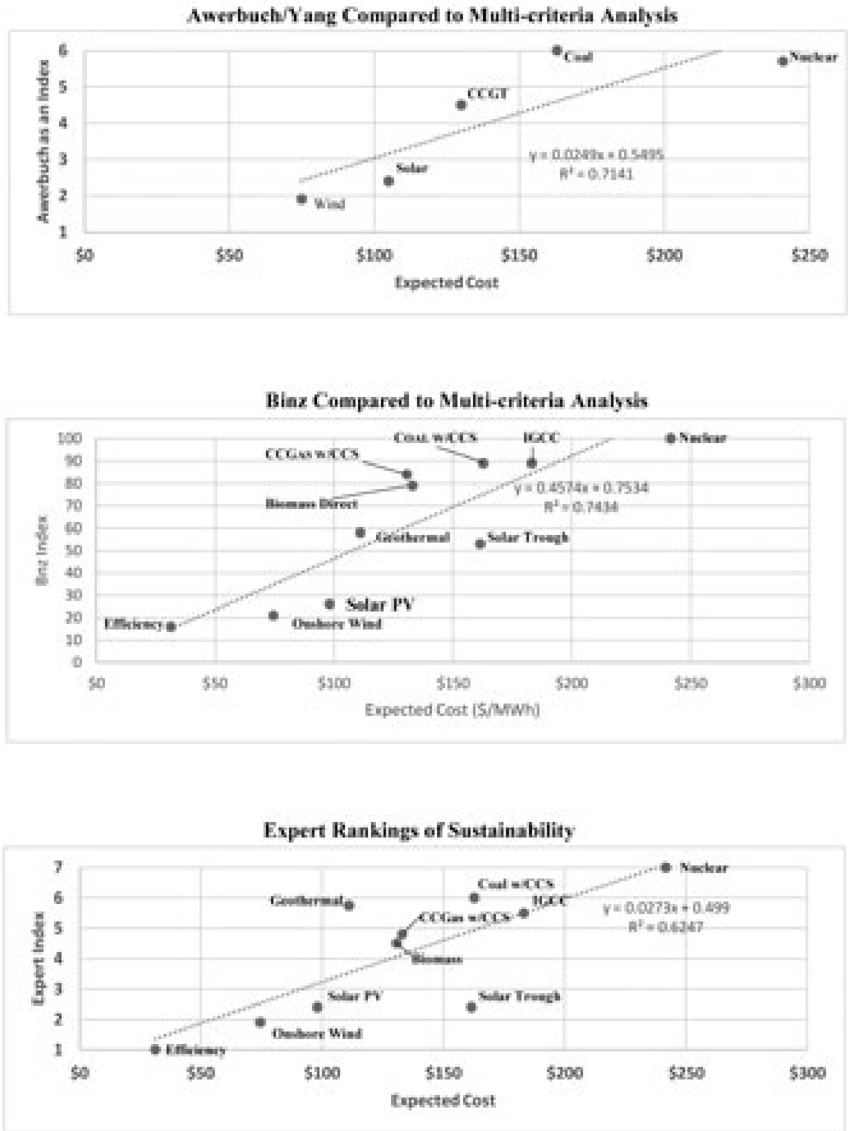


Figure 11.6 Multicriteria Portfolio Analysis Compared to Qualitative Ratings

Sources: Shimon Awerbuch and Spencer Yang, "Using Portfolio Theory to Value Power Generation Investments," in *Analytic Methods for Energy Diversity and Security,* ed. Morgan Bazilian and Fabien Rocques (Oxford, U.K.: Elsevier, 2008), 63, citing International Energy Agency/Nuclear Energy Agency, *Projected Costs of Generating Electricity* (Paris: OECD, 2005); Ron Binz, et al., *Practicing Risk-Aware Electricity Regulation: What Every State Regulator Needs to Know* (Boston, MA: Ceres, 2012).

CONCLUSION

This chapter demonstrates that a multicriteria portfolio approach to evaluating assets to decarbonize the economy shows that the "economic merit order" of resource acquisition is quite close to the "environmental merit order." Applying least-cost criteria in the context of a carbon constraint achieves the goal of pollution reduction.

- In the long-term, the economic and environmental "merit orders" are almost identical. Because the cost of the low-carbon, low-pollution technologies has plummeted and their cost is expected to continue to decline, the shift away from baseload resources (fossil fuels and nuclear power) to reliance on flexible renewable resources—linked with active management of supply and demand—will lower the cost of electricity.
- Even in the mid-term, the "economic merit order" follows the "environmental merit order" to a large extent (75–90 percent, depending on costs used). Because the deviation of the "environmental merit order" is so small and the economic benefit of pursuing a 100 percent renewable electricity sector is so large, it does not seem worthwhile to relax the carbon or the other pollutant constraints.
- In the short-term, the main resources of the 100 percent renewable approach are currently less costly and widely available. Therefore, there is no reason to hesitate in pursuing the low-carbon, low-pollution path.

As noted in the introduction, the economics of decarbonization are a solid platform on which to build the political economy of the management of global climate change. While technoeconomic factors are extremely important, economics do not guarantee success. Governance structures are at least as important. The analysis of the economics identifies two key conditions for the Paris agreement—that decarbonization is affordable and therefore not antithetical to development and that diversity in resources requires flexibility in responses to negotiate between the horns of the climate change dilemma.

This analysis concludes that the political economy chosen for responding to climate change in the Paris Agreement fits the underlying technoeconomic nature of the available resources. It is also consistent with the terrain of political authority and responsibility of the Parties to the underlying United Nations Framework Convention on Climate Change. The political economy of the Agreement reflects the combination of technoeconomic conditions, environmental goals, and political reality.

- The progressive, mixed market economic model is driven by the need for a rapid, least-cost decarbonization that supports sustainable development of the global economy.
- It also recognizes vast differences in resource endowments and the dramatic differences in level of economic development between the Parties.
- The multistakeholder, commons approach to governance reflects the diversity of circumstances and the authority of nations over local energy policy.

The study of the governance structure, as it develops deserves at least as much attention in future research as does the study of the economics of resource selection. Indeed, the study of resource economics has received a great deal of attention in the past, while the governance issue has received much less. The fact that a broad outline for the governance structure has been laid down should focus more attention on this important topic

EPILOGUE: THE IMPORTANCE OF LOCAL SUPPORT FOR GLOBAL CLIMATE POLICY IF THE UNITED STATES FLIP-FLOPS ON THE PARIS AGREEMENT

THE CHALLENGE

The United States' threat to withdraw from the Paris Agreement[1] should be a great concern to those committed to dealing with climate change, not only because it would remove the second largest global carbon emitter from compliance with the treaty, but also because it would be a blow to the governance model adopted by the Paris Agreement.

Climate change is a global commons problem. Individual decisions to emit affect all people who live in the commons. However, individual emitters are responsible for dramatically different levels of cause and have very different levels of capability to respond. Moreover, there is no overarching authority to set limits and order actions. These three characteristics make a polycentric, multistakeholder, collaborative governance structure necessary.[2] The structure the parties arrived at in Paris reflects well-known and proven principles of "common pool resource management," like the remarkably successful Internet multistakeholder model.[3]

In this model, legitimacy is built through the consensus process and norms of reciprocity and responsibility.[4] Having the second largest emitter and one of the key participants in putting the structure together withdraw would be a serious setback.

Because the Paris Agreement recognizes the need for a consensual framework in which authority is dispersed, it reaches out to subnational entities. While it is states that typically sign treaties (a power reserved to the federal government under the U.S. Constitution), other governmental entities can have international relationships. The Paris Agreement gives this aspect as much attention as any other issue it dealt with. It recognizes and encourages the participation of other entities (31 times) including subnational entities (governmental and nongovernmental, 12 times) and encourages non-signatories (12 times) to participate through observer status (7 times).

In the circumstance where the United States withdraws from the Agreement, could this other approach have a meaningful impact? In other words,

> are there U.S. states that are likely to be in compliance with the Paris Agreement (disagreeing with the U.S. decision to withdraw) that would have a meaningful impact?

From the point of view of the Paris Agreement, climate policy, and individual states, this note shows that the answer is a resounding yes.

A decision to comply by local or regional entities with energy- and climate-making authority would send a strong counter message and significantly enhance the legitimacy of the Paris Agreement. There are indications that this could be the case.

U.S. STATES POTENTIALLY IN COMPLIANCE

Emissions

Many individual states in the United States already have plans on the books to reduce carbon emissions that would be compliant with the Paris Agreement. Ten states have joined over 150 subnational entities in the "Under 2 Coalition," which is committed to achieving the goal of the agreement. As shown Table E-1, these 10 states account for over 17 percent of U.S. emissions and 2 percent of global emissions. Taken together, they rank seventh in the world, ahead of Germany.

In fact, sixteen states and major cities, representing all or important parts of 18 states, have intervened in support of the Clean Power Plan (CPP). This group represents about a third of U.S. emissions. Moreover, three of the largest states among those who joined the "Under 2 Coalition" and intervened to support the CPP alone account for 11 percent of U.S. emissions, have sent a strong letter to the President-elect in regard to the Clean Power Plan (CPP).

Combining the "Under 2" and CPP groups would raise their share of emissions to almost 36 percent. The group of potentially compliant states is larger. Using rankings on efficiency and solar policy, we find that there are several other states that rank above the lowest ranked "Under 2" states that can reasonably be considered good candidates to be in compliance. The maximum potential compliant groups would be 25 states that account for 44 percent of U.S. emissions.

These potential groups represent substantial shares of global emissions, especially in the larger groups. They rank fourth or fifth as groups and account for 5 to 6.6 percent of global emissions.

These groups also represent a very substantial part of U.S. emissions. Their share of emissions is much smaller than their share of population and economic activity. This reflects both the nature of activity in the states and the track record of reducing energy consumption and emissions. They have much more aggressive efficiency, solar, and renewable policies in place.

Policy

There are clearly dramatic differences between the groups. The potentially compliant states have much higher rankings on efficiency (ACEEE) and solar policy. Their targeted Renewable Portfolio Standard (RPS) goals are three times as high. All but one of the 25 states with a high probability of compliance based on the efficiency/solar rankings have an RPS. Among those states, the range is 10–65 percent by 2025, with RPS targets in the range of 30%. The one state without an RPS already exceeds the average targets for the other states (Iowa = 37 percent). In contrast, among the states that are not good candidates for compliance, almost half have no RPS. The average target for the RPS for the lager groups is less than 10 percent.

Sixteen of the states identified above as potentially compliant with the Paris Agreement have intervened to defend the CPP. Joined by the largest cities in two additional states on the list of potentially compliant states (Pennsylvania and Colorado), large cities in two other states, not on the list (Florida, which ranks 24 on the combined ranking and Virginia, which ranks 34) have joined in the support for the CPP. In contrast, all twelve of the states suing to stop the CPP are in the "noncompliant group."

WHAT'S IN IT FOR THE STATES?

Thus, a significant number of states have expended considerable political and legal resources to take these actions. Why go to the trouble? There are both economic and political reasons.

Table E-1 Groups and Characteristics of Potentially Compliant States

U.S. Importance	Emissions 2014	ACEEE Rank	ACEEE Transp.	ACEEE Bldgs.	Solar Rank	Corp. Clean	RPS 2025	GDP bil.
Under 2 (10)	926.1	6.3	6.4	5.1	11.5	47.4	26.3	5,918.7
Other	4,476.3	29.9	2.8	4.1	29.6	37.0		
Under % of U.S.	17.1							33.2
U2 or CPP (21)	1,775.3		4.9	4.6		44.0	28.5	9,021.0
Other	3,627.1		2.4	4.0		35.0		8,792.6
U2 /CPP as %	32.9							50.6
Max Potential (25)	2,147.3	12.4	5.5	5.2	13.5	49.7	28.4	10,064.8
Other	3,255.1	37.1	1.9	3.5	36.6	30.0	7.5	7,748.9
Potential/U.S. (%)	39.7							56.5

Groups of States

Global Importance	Under 2	U2+CPP	Max Potential
Percent of Global Emission	2.6%	5.4%	6.6%
Combined Rank	7	5	4
Rank Ahead of	Germany	Russia	India

% of U.S. Fossil Fuel Production			
Oil	6	14	15
Coal	0	10	16
Gas	0	26	27

Sources: Under2 Coalition, http://under2mou.org/coalition/; Chris Mooney and Brady Dennis, "Even in States Suing over New Climate Regulations, Coal Use Is Shrinking," *Washington Post*, May 3, 2016, https://www.washingtonpost.com/news/energy-environment/wp/2016/05/03/nearly-every-state-suing-over-obamas-climate-plans-is-burning-less-coal-anyway/?utm_term=.617eaffe2859; Brent Kendal, "Coalition of 18 States to Move to Defend Carbon-Emissions Rules: Group Expected to Ask Court to Intervene in Lawsuit Challenging Greenhouse-Gas Regulations," *Wall Street Journal*, November 4, 2015, http://www.wsj.com/articles/coalition-of-18-states-to-move-to-defend-carbon-emissions-rules-1446613261; U.S. Environmental Protection Agency, "U.S. Greenhouse Gas Inventory Report: 1990–2014," 2015; U.S. Department of Commerce, Bureau of Economic Analysis, "Gross Domestic Product (GDP) by State," 2015; U.S. Census Bureau, "National Totals: Vintage 2015," 2016; Netherlands Environmental Assessment Agency, CO_2 *Time Series 1990–2014 Per Region/Country*, 2015; ACEEE, *State Energy Efficiency Scorecard*, 2016, http://aceee.org/state-policy/scorecard; Solar Power Rocks, *2016 United States Solar Power Rankings*, https://solarpowerrocks.com/2016-state-solar-power-rankings/; Clean Edge, *Corporate Clean Energy Procurement Index, State Leadership & Ranking*, 2016, http://cleanedge.com/reports/Corporate-Clean-Energy-Procurement-Index; Jocelyn Durkay, *State Renewable Portfolio Standards and Goals*, National Conference of State Legislatures, December 28, 2016, http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx; U.S. Energy Information Administration, Petroleum, Natural Gas, Coal, 2015, http://www.eia.gov/.

Economics

First, consensus on the causes and consequences of climate change has grown to near unanimity. Even without a precise and detailed theory or estimate, there is a growing belief that the problem is large and in urgent need of a solution. The commons literature teaches that responding to the externality does not require altruism, but a recognition of self and shared interests and an acceptance of responsibility.

Moreover, acting like a responsible user of the commons has been made easy by the dramatic decline in cost of low-carbon, low-pollution approaches to meeting the need for electricity on both the supply and the demand side. There is a widespread and growing understanding that the main building blocks of the alternative electricity system—efficiency, onshore wind, utility photovoltaics and storage—are already cost competitive with conventional fossil fuels and much lower in cost than nuclear (new or aging). Cost trends suggest that the palate of cost competitive options is expanding quickly.

Within the United States, the political economy of this economic transformation is striking. The states identified as potentially compliant account for just 16 percent of the output of coal, 15 percent of oil and a little over 27 percent of the output of oil and natural gas. This is not a war against coal, but a battle between two very different paths to the future. With a few exceptions, the line between the potentially compliant states and the non-compliant states market the main front in the war.

It would be nice, but naïve, to assume that each individual state can pursue its own policy. Unfortunately, institutional structure and economics teach otherwise.

From a policy point of view, while the states have ultimate authority for rate setting and resource selection, the federal government has become deeply involved through oversight of the interstate grid, cross state environmental impacts, federal preemption of efficiency standards, federal subsidies for energy infrastructure and institutions, and so on. Simply put, as noted above, policy and subsidies created the huge incumbent infrastructure and policy is necessary to transform it.

From an economic point of view, there are other externalities that are important, as noted above. Economies of scale and learning will be greater if the total market is larger. The coordination of resources across the interstate grid is an important factor that affects the economics of the alternative system. Consumption externalities are also important, particularly for natural gas and oil. The greater the reduction in consumption, the greater the downward pressure on prices. This increases the disposable income of households.

Politics

At the outset, the political discussion must note that there is growing public support for action, even in the United States. More than 60 percent of respondents to polls, across the states and political parties, support reduction in emissions through regulation.[5]

The state-specific issue flows from the federal-state relations, mentioned above. For states this is a central consideration. Beyond the important interconnection between federal and state policy notes above, federalism plays an important role in energy policy. The right of independent state action is important to many states.

Central energy policies, like building codes, utility efficiency programs, and renewable portfolio standards, are state-based. However, some broader policies are formally tied up in the federal-state nexus. The federal government has preempted state action on appliance efficiency standards, where the federal government has acted. It does the same for environmental regulation, except that California can take independent action (with a waiver from the federal government). Other states can choose to follow either the federal standard or the California standard.

The Clean Cars Program is a good indicator of the importance of this state action. Of the 24 states counted as potentially compliant, 15 were members of the Clean Cars Coalition, which adopted California's auto standard. Six other states had similar auto commitments or moved toward Clean Cars participation. The current number of participants is smaller. A demonstration of the importance of this federalism principle can be found in the development of the hybrid vehicles. California's insistence on the development and deployment of a low emissions vehicle played a key role in instigating the development of the hybrid.

Thus, potentially compliant states have a clear political interest in asserting and preserving their right to act independently, not to mention a strong interest in moving policy in a direction that serves their direct economic interest and the interest of the participants in the global climate commons.

CONCLUSION

If this split in the United States spills over into the international arena, it would have a significant impact, not simply on the percentage of emissions striving to be in compliance with the Paris Agreement, but also as a political/policy message. A decision to comply by local or regional entities with energy- and climate-making authority would send a strong counter message and significantly enhance the legitimacy of the Paris Agreement.

Collaborative governance of common pool resources is dependent on the voluntary compliance of the participants. Whether or not the potentially compliant states seek formal standing as observers, their public commitment to the goal and their defense of their right to comply as subnational entities would be an important contribution to the legitimacy and authority of the agreement. Should the U.S. federal authority decide to withdraw, the participants to the Agreement might sanction noncomplying parties, which is an important part of eliciting compliance in common pool resource governance. They could exempt compliant subnational entities from those sanctions, which would send an extremely powerful message.

The principle of graduated sanction is central to establishing effective governances of common pool resource management regimes. A successful reaction to the threat of U.S. withdrawal from the treaty—either through domestic U.S. resistance that prevents it or international sanctions for non-compliance/rewards for compliance that reverse it—might provide a critical test that determines the efficacy and legitimacy of global climate policy.

As noted in the introduction, the economics of decarbonization are a solid platform on which to build the political economy of the management of global climate change, and the Paris Agreement is the correct governance platform. While technoeconomic factors are extremely important, economics do not guarantee success. Governance structures are at least as important. The analysis of the economics identifies two key conditions for the Paris agreement—that decarbonization is affordable and therefore not antithetical to development and that diversity in resources requires flexibility in responses to negotiate between the horns of the climate change dilemma.

This analysis concludes that the political economy chosen for responding to climate change in the Paris Agreement fi s the underlying techno-economic nature of the available resources. It is also consistent with the terrain of political authority and responsibility of the Parties to the underlying United Nations Framework Convention on Climate Change. The political economy of the Agreement reflects the combination of techno-economic conditions, environmental goals and political reality.

- The progressive, mixed market economic model is driven by the need for a rapid, least-cost decarbonization that supports sustainable development of the global economy.
- It also recognizes vast differences in resource endowments and the dramatic differences in level of economic development between the Parties.

- The multistakeholder, commons approach to governance refl ect the diversity of circumstances and the authority of nations over local energy policy.

The study of the governance structure, as it develops deserves at least as much attention in future research as does the study of the economics of resource selection. Indeed, the study of resource economics has received a great deal of attention in the past, while the governance issue has received much less. The fact that a broad outline for the governance structure has been laid down should focus more attention on this important topic

APPENDIX I: DEMOCRATIC EQUALITY AND THE ENCYCLICAL ON CLIMATE CHANGE AS PROGRESSIVE CAPITALISM

Focus	Social Purpose	Income Level	Threat/Problem	Policy Tools/ Remedies	Derivative & Complementary Effect
Democracy[1,A]	Collective self-determination by means of open discourse among equals,[5] Cooperative[6] social experimentation[9,B]	All the way	Oppression,[AA] Lack of Respect[AB] Reciprocation[AC]	Pure procedural justice[2,BA] & Substantive outcomes,[4,BB] Institutions for discovery Discussion, decision, voting,[7,BC] dissent[8,BD]	Humanitarian impulse,[3] Unfairness of bad luck
	Social relations of equality[10] Social basis of equal standing[11,C]		Segregation[12,AD] Disrespect, Shunning	Integration	Social basis of self respect[13]
	Epistemic justice[14] to create institutions to foster norms[16] of communicative justice[18,D] & expand scope of prosocial norms[20,E]		Prejudicial exclusion from meaning making activities[19,AE]	Education,[BE] Integration[15]	Value-based individual action[17]
Property[21,F] owning markets[29]	Individual & Collective responsibility,[25,G] Agency[26,H] Recognize role of capital labor & firms,[34,I] Understand capitalism's dynamism,[37] progress,[40,J] & risk management[41,K]	All the way & Global[30]	Inadequate surplus[22,AF] Misallocation of risk & reward[31,AG] Market failures[35] & behavioral factors[38,AH]	Division of Labor,[23,BF] Careful[24] range constraint,[27,BG] Progress[28,] Workplace governance[32,BH] Rich opportunity set[36,BI] Proper role of state & corporations[39,BJ]	Keynesian demand sufficiency Avoid stigma and pity[33]

Equality[42,L]	Entitlements set the thresholds[43,M] to achieve Autonomy, Equal Standing, Reciprocity,[47] & Personal Independence[50,N]	Bottom	Poverty[44,AI] Subordination Insufficiency[48,AJ]	Distribution through the division of labor,[46,BK] Redistribution through the development of human capital[49,BL] & the safety net[51,BM]	Distributive fairness[45]
Independence	Ensure freedom to choose[52,O] Promote Solidarity & Community	Middle	Insecurity,[53,AK] Segregation	Social Insurance (risk pooling)[54] as an entitlement[55]	Prevent envy
Constrain Inequality[58,P]	Promote Solidarity & Community,[Q] Prevent leverage for advantage[59,R]	Top	Hierarchy,[56,AL] Segregation Avoid plutocracy[60,AM]	Taxation,[57,BN] Campaign spending limits,[BO] Integration	Promote mobility Prevent envy

Legend: Numbers are references to various articles by Elizabeth Anderson, see bibliography for complete information. Letters are references to Pope Francis, *Laudato Si'*, Encyclical letter on care for our common home, June 18, 2015.

SOURCES AND NOTES

1 To realize the epistemic powers of democracy, citizens must follow norms that welcome or at least tolerate diversity and dissent, that recognize the equality of participants in discussion by giving all a respectful hearing, regardless of their social status, and that institute deliberation and reason-giving, rather than threats and insults, as the basis of their communication with one another. An epistemic analysis of democracy helps us see that it is not just a matter of legal arrangements. It is a way of life governed by cultural norms of equality, discussion, and tolerance of diversity. Elizabeth Anderson, "The Epistemology of Democracy," *Episteme* 3 (2006).

2 A system of pure procedural justice might include only purely procedural rules, as in libertarian systems of laissez faire capitalism. Alternatively, they could contain both purely procedural rules and range-constraining rules, as Rawls's theory of justice. . . . We need a theory of pure procedural justice that contains range-constraining rules. Elizabeth Anderson, "How Should Egalitarians Cope with Market Risks?" *Theoretical Inquiries in Law* 9 (2007): 240, 241.

3 The inequalities at stake are not instituted for the sake of discriminating against less-preferred people, but to provide the price signals needed to direct people's choices in developing and exercising their talents in ways that are valued by others. Since such direction is inherent in the ideal of society as a system of cooperation among equals, it is hardly morally arbitrary, even if it results in distributive patterns that track morally arbitrary of birth to some degree. . . . The value of distributions is merely derivative of the value of social relationships, and tied to the right rather than the good. Elizabeth Anderson, "Expanding the Egalitarian Toolbox: Equality and Bureaucracy," *Proceedings of the Aristotelian Society* 82 (2008): 260–261.

4 There is a longstanding tension in democratic theory between accounts of success that are internal and external to the democratic decision-making process. Internalists, or proceduralists, hold that, to vindicate a decision-making process, one need only show that it is procedurally fair. This position neglects the instrumental functions of democracy. If we decide that a problem, such as air pollution, is of public interest and that dealing with it requires joint action under the law, we don't just flip a coin to decide what pollution laws to enact, even though this would be procedurally fair. Rather, we will judge the success of democratic institutions according to criteria that are (partially) external to the decision-making process: do the pollution laws enacted actually reduce pollution to acceptable levels, at an acceptable cost? The *ex ante* popularity of a law—its approval by a majority—may make its enactment legitimate. But that does not ensure that the law will be successful. Whether the law succeeds in solving the problem for which it was drafted depends on its external consequences—not, or not simply, on the fairness of the procedure by which it was enacted. . . . Hence, the criteria of success for democratic institutions are partly internal and partly external to the decision-making process. Anderson, "Epistemology of Democracy," 11.

5 Voters are not to ask themselves what priorities they give to different capabilities for citizenship in their private choices, but what priorities they want the state to assign to these different capabilities, given that these goods shall be provided in common. . . . Most people gain much more from other people's freedom of speech than from their own. Elizabeth Anderson, "What Is the Point of Equality?" *Ethics* 109 (1999): 332.

6 In defining principles for a just division of labor and a just division of the fruit of that labor, I want to contrast this image of joint production with the more familiar image that invites us to regard the economy as if it were a system of self-sufficient Robinson Crusoes, producing everything by themselves until the point of trade. By "joint production," I mean that people regard every product of the economy as jointly produced by everyone working together. Anderson, "What Is the Point," 321; Anderson, "Expanding the Egalitarian Toolbox," 264–265.

7 Voters are not to ask themselves what priorities they give to different capabilities for citizenship in their private choices, but what priorities they want the state to assign to these different capabilities, given that these goods shall be provided in common. . . . Most people gain much more from other people's freedom of speech than from their own. Anderson, "What Is the Point," 332.

8 A free press, public discussion and hence mutual influence prior to voting are constitutive, not accidental features of democracy. Without access to public fora for sharing

information and opinions beyond their immediate knowledge, voters are uninformed and often helpless. Democratic decision making needs to recognize its own fallibility, and hence needs to institute feedback mechanisms by which it can learn how to devise better solutions and correct its course in light of new information about the consequences of policies. Periodic elections are one critical feedback mechanism of this sort. . . . Diversity and disagreement are central features of democracy. An adequate epistemic model of democracy needs to represent its functions at all stages of decision making: during deliberation, at the point of decision (voting), and after a decision has been made. . . . Most importantly, Dewey's experimentalist model of democracy helps us see the epistemic import of several democratic institutions that sustain its dynamism, its capacity for change: periodic elections, a free press skeptical of state power, petitions to government, public opinion polling, protests, public comment on proposed regulations of administrative agencies. In Dewey's model, these are mechanisms of feedback and accountability that function to institutionalize fallibilism and an experimental attitude with respect to state policies. They push governments to revise their policies in light of evidence—public complaints, as expressed in both votes and discussion—that they are not working, or expected not to work. On Dewey's model, votes and talk reinforce one another, the votes helping to insure that government officials take citizens' verbal feedback seriously, the talk helping to define and articulate the message conveyed by votes. . . . Dewey stressed that for democracy to work, it was not enough simply to institute. For this reason, individuals must be free to dissent not just at the voting stage, but after a decision is made. This requires institutionalization of a "loyal opposition." Without an opposition to remind the public of continuing objections to collective decisions, and to pose alternatives, accountability of decision makers is impossible. Nothing would force decision makers to reconsider their decisions. Only with such continuing opposition can fallibilism and the institutional capacity for experimentation—revising one's decisions on the basis of experience with their consequences—be realized. Anderson, "Epistemology of Democracy," 13, 15, 16, 17.

9 Somehow, information in the heads of many disparate actors must be brought to bear on the solution to the problem. Different institutions can be evaluated according to their ability to mobilize and respond to the required information. The only adequate vehicle for transmitting the required information is market prices. Markets uniquely generate and transmit the required information; central planners have no market-independent access to it. Hence, the problem of resource allocation should be assigned to markets, not to states. . . . Socially dispersed information can be transmitted in three forms: talk, votes, and market prices. Markets respond primarily to price information; democratic states primarily to talk and votes. . . . The epistemic needs and powers of any institution should be assessed relative to the problems it needs to solve. Let us therefore begin with a sketch of the characteristics of problems democratic states need to solve. These are problems (a) of public interest, the efficient solution to which requires (b) joint action by citizens, (c) through the law. The last two conditions indicate why the solution cannot be left up to the unregulated voluntary choices of individuals or private associations. The first sets a constraint on what problems may be legitimately assigned to state action. . . . Prices transmit information about private preferences. But as we have seen from the religious case above, the mere fact that a private preference is widely held does not make it a public interest. Talk is needed to articulate proposals to make certain concerns a matter of public interest; votes are needed to ratify such proposals. . . . Dewey took democratic decision making to be the joint exercise of practical intelligence by citizens at large, in interaction with their representatives and other state officials. It is cooperative social experimentation. Anderson, "Epistemology of Democracy," 9, 10, 14.

10 When we reconceive equality as fundamentally a kind of social relationship rather than a pattern of distribution, we do not abandon distributive concerns. Rather, we give such concerns a rationale. Some goods, such as basic liberties and rights to vote, bring legal suits, and testify in court, need to be distributed equally because equal distributions are constitutive of equal social relations. People need adequate levels of other goods, such as income and wealth, so as to be able to avoid or escape oppressive social relations, and to participate in all domains of social life as an equal—which means (in part) without shame or stigma, and with the human, social, and cultural capital needed to perform adequately in those domains. Ceilings

on distributive inequality may be necessary to avoid the conversion of wealth into social inequality. For example, progressive income and inheritance taxes may be needed to prevent the rich from capturing formally democratic institutions and turning the state into a plutocracy. Such considerations give us instrumental reasons to promote more equal distributive patterns. Distributions may also be objectionable if they are caused by oppressive social relations. Anderson, "Expanding the Egalitarian Toolbox," 143.

11 I prefer to speak of "social bases of equal standing," where equal standing is understood as a complex functioning. Elizabeth Anderson, "Defending the Capabilities Approach to Justice," in *Measuring Justice: Primary Goods and Capabilities*, ed. Harry Brighthouse and Ingrid Robeyns (Cambridge, U.K.: Cambridge University Press, 2010), 99.

12 Categorical inequalities across all three dimensions: Economic based on opportunity (hoarding, leverage marginalization, exploitation); Political based on powerlessness (violence, oppression). Social based on segregation (spatial and role), Psychological (including stigmatization, stereotyping, prejudice); and Intergroup process (emulation, adaptation). Elizabeth Anderson, *The Imperative of Integration* (Princeton, NJ: Princeton University Press, 2010), 7–16. Stigmas and stereotypes, discourse inequality, shunning and the like are undemocratic aspects of civil society. Anderson, "Defending the Capabilities Approach," 90.

13 Rawls considered the social bases of self-respect to be the most important primary good. He hoped that a just allocation of other primary goods—basic liberties, job and educational opportunities, income and wealth—would be sufficient to secure the social bases of self-respect for all. Anderson, "Defending the Capabilities Approach," 90.

14 We could say that the virtue of epistemic justice for institutions is otherwise known as epistemic democracy: universal participation on terms of equality of all inquirers. Elizabeth Anderson, "Epistemic Justice as a Virtue of Social Institutions," *Social Epistemology* 26 (2012): 172.

15 Structural injustices call for structural remedies. . . . Group integration is a structural remedy. When social groups are educated together in terms of equality, they share educational resources and thus have access to the same (legitimate) markers of credibility. When they engage in inquiry together, on terms of equality, members of disadvantaged groups can gain epistemic favor in the eyes of the privileged. . . . Shared inquiry also tends to produce a shared reality. Anderson, "Epistemic Justice," 171.

16 The great puzzle of social norms is not why people obey them, even when it is not in their self-interest to do so. It is, how do shared standards of conduct ever acquire their normativity to begin with? . . . Most people's identities are largely, although not exclusively, constituted by their membership in social groups or collective agents. Theories of collective agency have recently enjoyed a great revival. . . . A member's commitment to advance organizational goals is conditional on enough of the others doing their part to sustain an understanding that the members really constitute a coherent group. In the standard employer-employee relationship, the employee's commitment is conditional on the employer's playing his part, which includes paying compensation for work performed. Compensatory incentives may be needed to recruit willing people into organizational roles. . . . In jointly accepting the principle of action, each member of the group regards herself as committed to doing her part in upholding the principle *with the others*. To regard *us* as being jointly committed to a principle is to regard each of us as thereby having a reason to comply, *and* to accept that everyone is accountable to everyone else with respect to compliance. The normativity or "oughtness" of social norms, then, is an "ought" constitutive of commitments of collective agency. It is grounded in the perspective of collective agency, in "our" shared view of how "we" ought to behave. It is based on the fact that members accept the authority of "us" to determine how each should behave in the domain defined by the norm. Elizabeth Anderson, "Beyond *Homo Economicus*: New Developments in Theories of Social Norms," *Philosophy and Public Affairs* 29 (2000): 191, 192, 193.

17 We should not think of structural remedies as *competing* with virtue-based remedies for epistemic justice. Many structural remedies are put in place to enable individual virtue to work, by giving it favorable conditions. . . . Moreover, structural remedies may be viewed as virtue-based remedies for collective agents. . . . When the members of an organization jointly commit themselves to operating according to institutionalized principles that are designed to achieve

testimonial justice, such as giving hearers enough time to make unbiased assessments, this is what it is for the organization itself to be testimonially just. Anderson, "Epistemic Justice," 168–169.

18 A transactional theory of justice identifies criteria for particular exchanges or interactions between one person and another. . . . The cumulative effect of how our epistemic system elicits, evaluates, and connects countless individual communicative acts can be unjust, even if no injustice has been committed in any particular epistemic transaction. Nor can we count on the practice of individual epistemic justice to correct for all of these global effects. Rather, the larger system by which we organize the training, uptake, and incorporation of individuals' epistemic contributions to the construction of knowledge may need to be reformed to ensure that justice is done to each knower, and to groups of inquirers. Anderson, "Epistemic Justice," 164–165.

19 Testimonial exclusion becomes structural when institutions are set up to exclude people without anyone having to decide to do so. . . . By contrast, hermeneutical injustice is always structural. Hermeneutical injustice occurs when a social group lacks the interpretive resources to make sense of important features of a speaker's experience, because she or members of her social group have been prejudicially marginalized in meaning-making activities. Anderson, "Epistemic Justice," 166.

20 The optimistic tale represents capitalism as expanding the scope of cooperation and trust by enabling people to reap gains from trade worldwide, bridging parochial divisions of nationality, religion, and ethnicity. Capitalism is an engine of cosmopolitanism, cooling socially dangerous passions such as religious fanaticism, and overcoming xenophobia. The impersonality, anonymity, and openness of markets to all comers is favorably contrasted with social orders in which people are tightly constrained by parochial connections and loyalties of family, ethnicity, and neighborhood. Both stories recognize that free markets cannot function efficiently on the basis of self-interest alone. Many contracts, especially labor contracts, are incompletely enforceable. If people were not willing to work harder than self-interest required, and if employers were not willing to reward workers for such extra effort, many potential gains from trade could not be reaped. Moreover, markets are efficient only to the extent that participants accept the rules of the game. Once people extend self-interested reasoning to consider whether they should lie, cheat, and steal, market transactions become very costly or break down. Elizabeth Anderson, "Beyond *Homo Economicus*," 196.

21 From an egalitarian point of view, property rights are artificial, *all the way down*. A primary role of the state in a market egalitarian system is to *define* a system of artificial property rights that realizes the freedom and equality—which is to say the personal independence–of each individual in it, to the extent possible. . . . "Tax and transfer" programs, such as social security and universal health care, and "interference" with the market, such as minimum wages, are construed, from the point of view of what Rawls called a "property-owning democracy," as simply another form of artificial property right added to others, such as patents, copyrights, and rights to the broadcast spectrum, that are obviously artificial. Elizabeth Anderson, "How Should Egalitarians Cope," 243.

22 Market democracy is a fresh, important research project. At the level of ideal theory, high liberals made a serious error in discounting the importance of private enterprise and economic agency. Market democracy promises to correct this error. To move forward, it needs a better map of social possibilities that acknowledge the ubiquity and dangers of market-generated collective action problems and authoritarian private government. Elizabeth Anderson, "Recharting the Map of Social and Political Theory: Where Is Government? Where Is Conservatism?" *Bleeding Heart Libertarians*, June 2012, p. 4.

23 Republicans offered a sharp (and utterly non-Marxist) critique of the governance of workers by their bosses. Their critique was largely forgotten because they failed to offer a feasible remedy to the problems they identified in the system of wage labor. Nevertheless, republican principles of constitutional design offer some insights into possibilities for a constitution of liberty in the workplace. . . . Thus, in republican theory, the rule of law secured citizens against arbitrary rule by the state; private property secured free individuals against the arbitrary rule of any private person; and elections made rulers accountable to citizens and thereby made

the affairs of state a matter of public interest, rather than the private concern of state officials. Classical republicanism presupposed social hierarchy, class privilege, slavery and subjection. To the extent that it cared for equality, it was only among the free, who jealously guarded their independence against threats of domination by other free people. . . . Commercial republicanism offers a moderate variant. . . . Workers' liberation from "servile dependency upon their superiors," along with good government, is "by far the most important" of the effects of commercial society. Elizabeth Anderson, "Equality and Freedom in the Workplace: Recovering Republican Insights," *Social Philosophy and Policy* 31 (2015), 3, 5, 7.

24 Moreover, democratic equality can make access to certain functionings—those requiring an income—conditional upon working for them, provided that citizens have effective access to those conditions—they are capable of performing the work, doing so is consistent with their other duties, they can find a job, and so forth. Anderson, "What Is the Point," 318.

25 Any theory of distributive justice entails assignments of weak substantive responsibility, making some issue a matter of collective responsibility, in which we share our fates and others a matter of individual responsibility, with respect to which each individual is on her own. Anderson, "How Should Egalitarians Cope," 244.

26 Principles of justice should honor people's concern for the self-respect they attain through their agency; that they not only enjoy certain outcomes, but do so through their own activities. The economy is an important domain of agency. Anderson, "Recharting the Map," 1.

27 We need rules . . . which allow market forces, and hence luck, to influence distributive outcomes, but only within an acceptable egalitarian range. The ideal of equality in social relations helps us devise acceptable constraints at the top, bottom, and in the middle. Anderson, "How Should Egalitarians Cope," 239.

28 For societies that lack the resources to meet all the thresholds for all persons for all relevant functionings, some additional principles would have to be specified in advance to determine whose and which capability deprivations should be given priority. It would make sense to give priority to functionings that are prerequisites to others (e.g. those urgently needed for survival, such as basic nutrition, health, and safety) and then to choose those that enable individuals to acquire the others for themselves (e.g. education over housing, if the housing suffices for survival, and if education makes the individual better equipped to improve their housing). Developed countries, while they also face trade-offs, are not so evidently constrained by specific demands of justice, supposing all have reached the relevant thresholds. Whether more resources should be devoted to health care, say, or education is open to policy choices, with a wider range of reasonable answers. Anderson, "Defending the Capabilities Approach," 98. The sufficiency levels . . . in a prosperous society, may be quite high. Anderson, "Defending the Capabilities Approach," 84. Several developments motivated the development of systemic theories of justice. Economists developed an understanding of the economy as a system of interconnected mechanisms that led to aggregate outcomes that were not intended by any individual, but which could be predictably affected by state policies. With power comes responsibility. As economies became richer, the capacity of states to regulate distributions systemically grew, as did public demand for such policies. With economic growth spurred by the Industrial Revolution, the economy had the productive capacity to overcome mass poverty. Elizabeth Anderson, "Thomas Paine's 'Agrarian Justice' and the Origins of Social Insurance," in *Ten Neglected Classics of Philosophy*, ed. Eric Schliesser (New York, NY: Oxford University Press, 2017), 11.

29 "Desert-catering luck egalitarians . . . theories fail because considerations of market efficiency, freedom and dignity undermine the claims of desert to inform standards of just for society as a whole." Anderson, "How Should Egalitarians Cope," 239.

30 I shift from talk of "citizen" to talk of "workers" in part because the moral implications of regarding the economy as a system of cooperative production cross international boundaries. As the economy becomes global, we are all implicated in an international division of labor subject to assessment from an egalitarian point of view. We have obligations not only to the citizens of our country but to our fellow workers, who are not found in virtually every part of the globe. We also have global humanitarian obligations to everyone considered simply as human beings. Anderson, "What Is the Point," 321. At the level of international justice, too, individuals owe it to one another not to uphold international coercive and cooperative order that is harmful to oth-

ers' objective interests, or that deprives them of their basic needs, when there is a feasible alternative that would secure those needs for all. Anderson, "Defending the Capabilities Approach," 86.

31 In regarding the division of labor as a comprehensive system of joint production, workers and consumers regard themselves as collectively commissioning everyone else to perform their chosen role in the economy. In performing their role in an efficient division of labor, each worker is regarded as an agent for the people who consume their products and for the other workers who, in being thereby relieved from performing that role, become free to devote their talents to more productive activities. . . . Any consideration offered as a reason for a policy must serve to justify that policy when uttered by anyone to anyone else who participates in the economy as a worker or as a consumer. . . . These consumers are not free to disclaim all responsibility for the bad luck that befalls workers in dangerous occupations. For they commissioned these workers to perform those dangerous tasks on their own behalf. The workers were acting as agents for the consumers of their labor. It cannot be just to designate a work role in the division of labor that entails such risk and then assign a package of benefits to perform in the role that fails, given the risk, to secure the social conditions of freedom to those who occupy the role. Anderson, "What Is the Point," 322–323.

32 Modern production involves the use of large-scale equipment and infrastructure, such as assembly lines, airports, and banks, that cannot be divided up and independently operated by individual workers, but which can only be used by teams of closely cooperating workers. No set of contracts, however detailed, can successfully coordinate all stages of production. In a production process with a complex division of labor, innumerable contingencies arise that require workers to alter their routine. Who should do what if the machine breaks down, if a co-worker fails to show up, if too many customers are waiting in long lines? It is not merely costly but impossible to specify all contingencies in detailed labor contracts. Firms arise at the point where production requires closely coordinated and open-ended cooperation, and complete contracts cannot be drawn. These considerations help explain the boundary between the market and the firm, between contract and governance. They do not explain why that governance is hierarchical. . . . While efficiency considerations may require some form of hierarchy, they do not entail that those in authority exercise arbitrary power over their workers, entitled to issue any orders other than to commit crimes, on pain of job loss. While participatory democracy may be inefficient, it does not follow that the workplace cannot be governed as a representative democracy, with workers electing managers, and managers limited by rule-of-law constraints on the orders they issue to workers. Efficiency considerations underdetermine the constitution of workplace governance. Elizabeth Anderson, "Equality and Freedom in the Workplace: Recovering Republican Insights," *Social Philosophy and Policy* 31 (2015): 10. A third option would enhance the voice of workers in the constitution of legislative power within the firm (Locke's condition 3). Numerous managerial decisions involve legitimate tradeoffs between productive efficiency and workers' liberties that could not be handled by a bill of rights. Because employers exercise market power over workers, any workplace authority vested exclusively in management will not give sufficient weight to workers' interests. Vesting authority exclusively in workers may not give sufficient weight to the interests of the owners of a firm. Republican theorists argued that, in societies composed of distinct classes, the best form of government would be "mixed"—that is, vest each class with distinct authority. . . . I have argued that the prevailing discourse of liberty and equality in the domain of work misrepresents the issues, because it conflates markets with production, contracts with governance. Neither the doctrine of liberty of contract, nor *a priori* theories of property rights, offer sound ways to balance managerial authority and workers' liberty. The question is about constitutional design for legitimate workplace government. I have suggested that, despite their failure to come to terms with the necessity of hierarchy in governing large-scale productive enterprises, republican theories of constitutional design, focused on limiting authority in the interest of freedom-as-nondomination, remain relevant for devising solutions to the problem of workplace governance. If this is so, then limits on social inequality are necessary for freedom. Elizabeth Anderson, "Equality and Freedom," 15.

33 Democratic equality calls for raising the income of low-wage workers in part on grounds of their entitlements as citizens, and in part on the ground that they play an underappreciated

role in the economy, regarded as a system of joint production: by devoting themselves to the tasks that command a low market wage, they free others to exercise their talents in more productive ways. This rationale for narrowing income gaps does not inquire into whether people in low-wage jobs are there because they lack the talent to do better. Anderson, "What Is the Point," 7.

34 Neither the free market argument nor the liberal reply offer an institutionally adequate representation of the stakes in this dispute. Both accept a frame in which the critical issues are played out in negotiation over the terms of the labor contract. Neither side appears to notice that little negotiation takes place in most labor contracts. The typical worker, upon being hired for a job, is not given a chance to negotiate. Nor is she handed a contract detailing the terms of the deal. She is handed a uniform, or a mop, or a key to her office, and told when to show up. The critical terms are not even what is said, but what is left unspecified. *The terms do not have to be spelled out, because they have been set not by a meeting of minds of the parties, but by a default baseline defined by corporate, property, and employment law that establishes the legal parameters for the constitution of capitalist firms*. . . . Libertarians and liberal egalitarians have overlooked this point, because they share a defective representation of the institutional structure of capitalism: they conflate capitalism with the market, and therefore imagine that the labor contract is the outcome of market orderings generated independently of the state. State regulation of labor contracts is therefore seen by both as an "interference" with market orderings. They disagree only on whether this interference is justified. . . . Missing from this picture is capitalist firms, and the essential role of the state in defining their forms. Markets are not distinctive to capitalism; they exist in all economic systems more sophisticated than a hunter-gatherer economy. Capitalism is distinguished from other economic systems by its mode of production. *The labor contract is not properly seen as an exchange of commodities on the market, but as the way workers get incorporated under the governance of productive enterprises*. Employees are governed by their bosses. The general form of that government is determined by the laws of property, incorporation, and labor, not by contract. Elizabeth Anderson, "Equality and Freedom," 2.

35 Externalities, asymmetric information, and other collective action problems are even more pervasive in economic life. Countless ways of conducting business reap gains for some while imposing costs on others. . . . Workers would be *lucky* to get a contract of adhesion, with no terms open for negotiation, but at least all the terms specified. What they actually get is *arbitrary, authoritarian government, with open-ended terms of subjection*. Anderson, "Recharting the Map," 2.

36 A just regime should arrange the rules of economic life to ensure a rich set of opportunities for people to engage in market activities according to their preferences, consistent with honoring the self-authorship of others. This includes freedom to create, own, and operate private productive enterprises. Anderson, "Recharting the Map," 1.

37 Capitalism is an inherently dynamic economic system. It responds rapidly to changes in tastes, to new sources of supply, to new substitutes for old products. This is one of capitalism's great virtues. But this responsiveness leads to volatile prices. Consequently, capitalism is constantly pulling the rug out from underneath even the most thoughtful, foresightful, and prudent production plans of individual agents. Elizabeth Anderson, "How Not to Complain about Taxes (III): 'I Deserve My Pretax Income,'" *Left2Right*, January 26, 2005, 1. Four features distinguish Smith's vision from laissez-faire capitalism. (1) Economies of scale are rarely significant. The great virtue of free trade—the abolition of state granted monopolies, tariffs, and other protections–is not merely that it allocates resources more efficiently, but that it dissolves concentrations of wealth and thereby multiplies opportunities for independent producers. (2) The corporate form, and consequent importance of stock markets for raising capital, is sharply limited in scope. Smith criticized joint stock corporations for negligent mismanagement of stockholders' capital, conspiring to restrain trade, rent-seeking, and provoking foreign wars. He thought they were justified for only four types of routine, nonentrepreneurial business: banking, insurance, canals, and water utilities. These were the only businesses that required the huge concentrations of capital that joint stock corporations raise. (3) Labor markets are small. While not as hostile as radical republicans to wage labor, Smith's leading argument for the value of free markets in commercial society depends on their support for self-employment. Furthermore, his

critique of the stultifying effects of a fine-grained division of labor raises doubts about the value of scaling up production too far. The famous pin factory that Smith praised for its productivity-enhancing division of labor had only ten workers. Such small-scale enterprises could still support a robust republican culture of workers' independence, since they could be run on a collaborative basis. (4) Smith supported pro-labor state regulation: when a regulation of "the differences between masters and their workmen . . . is in favour of the workmen, it is always just and equitable." His example of a just labor regulation—requiring employers to pay workers in cash rather than in kind—illustrates the importance of regulating labor contracts for securing workers' independence. To be paid in goods chosen by one's employer is to submit to the employer's regulation of one's private life. . . . Capitalism and socialism are distinguished from these older property regimes by the large scale of productive enterprises, requiring a fine-grained division of labor *within* the firm. These property regimes facilitate capital concentration and vertical and horizontal integration. Both systems aim to reap the benefits of the Industrial Revolution, which realized immense productivity gains from increasing economies of scale. The distinction between capitalism and commercial republicanism is thus found not in free markets, but in the scale and structure of production. Capitalism is marked by the ubiquity of corporations (and similar forms of capital conglomeration, such as trusts), capital markets, and labor markets. Capitalism undermined the radical and commercial republican ideals by destroying their material basis in a self-employed workforce. It dramatically diminishes opportunities for individuals to attain independence by founding their own businesses. The overwhelming majority of workers are subject to their employer's governance. Elizabeth Anderson, "Equality and Freedom," 8, 9.

38 Orthodox rational choice theory attempts to explain social outcomes by assuming only the characteristics of *Homo economicus:* instrumental rationality and self-interest. Cast as methodological principles, these assumptions have considerable appeal. Methodological rationalism–the principle that we should try to explain people's actions as rational before resorting to explanations that represent them as irrational–is a sound starting point for social theory. The widespread normative appeal of the economic theory of rational choice therefore supports its use as the default theory for explaining human behavior. The theory can also be axiomatized and facilitates formal, quantitative modeling of human behavior. Methodological egoism—the principle that we should try to explain people's actions as self-interested before accepting their typically more flattering self-representations—supports the critical, unmasking function of social theory. Also, given that self-interest is one of our primary motives, a theory that could explain all human behavior without resort to other motivations could lay a claim to greater parsimony. How far do these assumptions advance our understanding before we must resort to alternative explanations? With respect to the hypothesis of expected utility maximization, the answer is: not far. We are not very good at judging probabilities; we do not think about risks in the way decision theorists think we ought; we do not order our preferences consistently; we care about sunk costs; and we systematically violate just about every logical implication of decision theory. There is probably no other hypothesis about human behavior so thoroughly discredited on empirical grounds that still operates as a standard working assumption in any discipline. This is not for lack of alternatives. Theories of bounded rationality, prospect theory, social rationality, and other alternatives are on hand. Elizabeth Anderson, "Beyond *Homo Economicus*," 172–173.

39 People can create property conventions and operate markets without relying on a state. It does not follow that capitalism needs the state only to enforce the property conventions and contracts that people devise independently of the state. Markets and property can exist without state action, but *capitalist* property and markets cannot. . . . Hernando de Soto makes the connections among formal (state-sanctioned) property, capitalism, and scale explicit in arguing that to enable their property to function as *capital,* as an asset that can be utilized to build wealth, people need the state to formalize their property rights. . . . Unified property records and standardization enable networks of cooperation and trade to be dramatically scaled up. The gains from secure and informed trade between distant people tend to be greater than between neighbors, because strangers are more likely to have access to different information, skills, and resources, and because they are more likely to have different tastes and face different relative prices for goods. . . . Corporate law provides the key to scaling up productive enterprises by

enabling the concentration of capital and close coordination of many workers. By standardizing the parameters of corporate governance—the rights and obligations of shareholders, boards of directors, and executive officers of a firm—corporate law enables multiple strangers to invest their money with confidence that their share will be protected, without having to pay high transaction costs in negotiating *ad hoc* governing arrangements with other shareholders, or retaining lawyers to advance their interests. It enables shares to be sold without buyers having to check the details of the corporate arrangement. Employment laws further define governance relations between managers and employees. Thus, the state is needed to supply the framework for the constitution of government for employees in a capitalist system. . . . Yet these republicans saw something that has been lost from the view of most mainstream libertarians: that hierarchical firms are distinct from markets, and often threaten the dignity and personal independence of workers. The common representation of the institutional structure of capitalism, which confuses hierarchies with markets, taints markets in the eyes of egalitarians, who are attuned to the humiliations and abuses many workers suffer on the job, while inducing many libertarians to turn a blind eye to what goes on there, on the assumption that it's all the product of consensual, negotiated agreements between the parties, an expression of inviolable property rights, or the efficient outcome of market competition. By exposing the coercive hand of the state in constructing workplace hierarchy, I hope to spur mainstream libertarians to scrutinize the workplace with a more critical eye, and be more open to constitutional reform of workplace governance. . . . I part ways with Carson's skepticism about efficiency gains from large-scale hierarchical production, however. While much of the abusiveness of hierarchy is an expression of bosses' love of dominion, and may even undermine efficiency, not all hierarchy is like this. I therefore call not for abolishing but for taming workplace hierarchy. Although the republican remedy against workplace hierarchy is not viable, republican ideas about constitutional design can help us think about where and how to draw the line between legitimate managerial authority and illegitimate domination. Elizabeth Anderson, "Equality and Freedom," 11, 13–15. In stressing the class-based origins of the capitalist transformation of credit, I want to emphasize that the extension of its benefits to wider classes of people was not the automatic result of the autonomous workings of markets. It was the product of protracted political action. . . . Once the demoralization of insolvency based on an appreciation of business cycles was invoked to allow wealthy capitalists off the hook, it was only a matter of time before less privileged classes would come to understand their predicament in the same terms and demand bankruptcy protection for themselves. This isn't laissez faire. It's the popular use of state power to extend the privileges enjoyed by capitalists to everyone else. Such preference changes, being endogenous to capitalist markets, are as much a part of the dynamic of capitalism as market exchange. The result of these changes in Western Europe was social democracy. This was not a repudiation of capitalism, but a fulfillment of the presuppositions of capitalist market exchange that Smith and Condorcet championed. Elizabeth Anderson, "Ethical Assumptions of Economic Theory: Some Lessons from the History of Credit and Bankruptcy," *Ethical Theory and Moral Practice* 7 (2004): 358.

40 Most critics of the normative framework of economic theory fault it for failing to recognize the vices of capitalism–for example, its inability to evaluate the inequality that capitalism generates. My thesis turns this critique on its head: the assumptions of economic theory fail to represent some of the *virtues* of capitalism. They fail to grasp some ways in which capitalism advanced freedom and equality. One way was by transforming the social relations of creditors to debtors. This enabled millions of people to obtain credit without having to give up their personal independence to or demean themselves before their creditors. The virtues of capitalism lie in the concrete social relations and social meanings through which capital and commodities are exchanged. Contrary to laissez faire capitalism, the conditions for sustaining these concrete capitalist formations require limits on freedom of contract and the scope of private property rights. . . . The kinds of freedom and equality that fundamentally matter, and that capitalism expanded, are embodied in concrete social relations governed by specific legal constraints and social norms. Freedom involves, at least, freedom from bondage to others. Equality involves a kind of social standing before others, premised on terms of interaction consistent with the dignity of both parties. Economic theory represents freedom and equality in abstraction from these concrete social relations. . . . It follows that the virtues of capitalism cannot be deduced from

the bare forms of private property and voluntary exchange. They depend on conditions not represented in the standard economic arguments for capitalism. These conditions often require constraints on the scope of freedom of contract and property rights, against the laissez faire ideal. . . . Capitalism enabled the mass of people to see themselves as *entitled* to respect and dignity in their commercial relations. This is the great cultural transformation marked by the transition from an aristocratic to a capitalistic ethic of credit. Once people see themselves as so entitled, they make use of the law to secure and extend these entitlements. The legal constraints on contract ensure that the workings of the market do not backslide into feudalism, that capitalism does not undermine its own cultural achievements. The form of capitalism they bring about is not libertarian laissez faire, but rather capitalism as we know it in the advanced democracies. . . . The classical economists had superior conceptions of freedom and equality, which are better able to grasp the specific virtues of capitalism. . . . To represent the specific virtues of capitalist transactions, freedom and equality must be understood in terms of the concrete social relations of the contracting parties during and after the exchange. A contract grounded in begging and self-debasement is not a contract among equals. A contract whose terms or remedies involve bondage or servitude does not realize the freedom of the parties. . . . Alternative systems of measuring welfare, such as the capabilities approach of Amartya Sen, could incorporate such important considerations as whether the contracting parties live at the mercy of their creditors or whether they can bargain for fair terms with dignity. Anderson, "Ethical Assumptions," 347, 357–358.

41 Until the late 18th century, theorists contemplated only local principles of justice. Several developments motivated the development of systemic theories of justice. Economists developed an understanding of the economy as a system of interconnected mechanisms that led to aggregate outcomes that were not intended by any individual, but which could be predictably affected by state policies. With power comes responsibility. As economies became richer, the capacity of states to regulate distributions systemically grew, as did public demand for such policies. With economic growth spurred by the Industrial Revolution, the economy had the productive capacity to overcome mass poverty. Finally, appreciation of the ways the competitive economic system could lay waste to individuals' best-laid plans, of how financial crises and unpredictable technological change could overwhelm the resources of the prudent and industrious, of how people's fates were closely connected apart from any contractual agreement, such that the conduct of others could bring not just great benefits but great harms to unrelated individuals, put enormous pressure on moralized conceptions of poverty. To those cast into involuntary unemployment by recession, into bankruptcy by financial panic, into sickness and disability by pollution and industrial accidents, nothing was more obvious than that their suffering was not their fault, not anything they deserved, nor something that they could hedge against with the resources at their disposal. The emerging market system was spectacularly productive and grew at unprecedented rates, but it also unleashed a "perennial gale of creative destruction" against which only the state could provide adequate shelter. Such calamities were not, in general, the product of local injustice in any particular transactions. Everyone could have dealt with one another with perfect propriety according to every local principle of justice, yet the cumulative effect of hundreds of thousands of locally just transactions could be disastrous. Paine understood this, insisting that "the fault . . . is not in the present possessors. . . . The fault is in the system." These considerations undermine the idea that the requirements of justice could be entirely satisfied by following local standards advanced without regard to their cumulative, systemic consequences. They undermine the idea of laissez-faire, of *unconstrained* pure procedural justice—the thought that just outcomes are whatever outcomes are produced by voluntary market transactions in a private property system based on "natural rights," letting the chips fall where they may. If justice requires state action, such as social insurance, to protect individuals against the "gale of creative destruction," then the state must be free to define *positive* (artificial, legal) property rights so as to enable such protection. A system of property rights must be justified systemically, in regard to its expected overall consequences. Anderson, "Origins of Social Insurance," 11. The great virtue of markets is that, in giving people the freedom to use their partial, situated knowledge according to their own judgments and tastes for risk, in response to market signals, they are able to effectively utilize essentially widely dispersed knowledge for the

advancement of others' interests. We share an interest in letting people act on their own judgments for how to use their knowledge, and what risks to take. We do not share an interest in having individuals make market choices according to social judgments of the most prudent choices that can be reasonably expected of them. This could only reflect the partial knowledge of some administrative board. Anderson, "How Should Egalitarians Cope," 249.

42 Equality refers fundamentally to the social relations in which we stand, and only derivatively to distributive outcomes. Anderson, "How Should Egalitarians Cope," 242. The proper negative aim of egalitarian justice is not to eliminate the impact of brute luck from human affairs, but to end oppression, which by definition is socially imposed. Its proper positive aim is not to ensure that everyone gets what they morally deserve, but to create a community in which people stand in relation of equality to others Anderson, "What Is the Point," 288–289. Expansive understanding of the social conditions of freedom. Anderson, "What Is the Point," 315. Social equals are regarded as *self-originating sources of claims*. . . enjoy *equal standing in discussions aimed at defining the terms of their interactions*. . . . live on terms of *reciprocity* with one another, none imposing conditions they would reject for themselves. . . enjoy *personal independence*, within a wide range, real freedom to lead their own lives according to their own judgments, without having to receive permission from others, justify the ideals and priorities they adopt to others, or submit to others' moralizing scrutiny. Anderson, "How Should Egalitarians Cope," 264–265.

43 From a systemic point of view, none of this makes sense. Market wages do not measure people's just deserts. Nor can the concept of desert, in the sense of something earned (presently or prospectively) by one's productive contribution or virtuous conduct, guide a systemic theory of justice. Think of the distributive system of the whole economy as like a ladder, with each rung designating a representative position in the system of social cooperation (including both market-compensated and uncompensated positions), the height measuring the expected income for that position. The concept of desert, merit, or qualification may coherently guide individual employers' assignments of particular workers to different market-compensated rungs in the ladder. But it says nothing about how high the lowest rung should be, or what considerations should guide the distance between the top and bottom rungs, or where those occupying positions outside the market should land. Here systemic considerations reign: not those of desert or merit, but of overall efficiency, utility, and, most importantly, systemic justice. Anderson, "Origins of Social Insurance," 12. The theory I shall defend can be called "democratic equality." In seeking the construction of a community of equals, democratic equality integrates principles of distribution with the expressive demands of equal respect. Democratic equality guarantees all law-abiding citizens effective access to the social conditions of their freedom at all times. . . . In such a state, citizens make claims on one another in virtue of their equality, not their inferiority, to others. Anderson, "What Is the Point," 289. In this second sense, the community of equals represents an ideal, not an absolute moral requirement. There will always be some individuals who lack the basic equipment to function effectively as an equal, or whose needs are so costly to satisfy up to threshold levels that compromises must be made. To see what compromises of this ideal are reasonable, we would have to go back to our contractualist framework and ask what compromises can be collectively willed—what compromises can be justified to everyone, especially those left worst off by them. Sen has shown that even some very poor societies have achieved impressive threshold levels of capability for nearly everyone. This suggests to me that, especially for very prosperous societies such as those in North America and Western Europe, it is reasonable to allow exceptions to the general demand for equality only at the margins. Anderson, "What Is the Point," 3. Democratic equality is egalitarian in its conception of just relationships among citizens, but sufficientarian in its conception of justice in the distribution of resources and opportunities. What is important is not that everyone has equal opportunities to acquire resources and fulfilling jobs, but that everyone has 'enough.' The ideal of democratic equality specifies how much this is: enough to secure the conditions of citizens' freedom and civic status as an equal to other citizens. On this view, as long as everyone has enough to function as an equal, inequalities beyond this threshold are not of particular concern. Anderson, "Ethical Assumptions," 106.

44 Egalitarians should not rest content with merely equalizing opportunities ex ante. While remaining indifferent to the drastic inequalities generated by unregulated markets ex poste.

Some outcomes are so bad that they are objectionable even if they are the consequence of voluntary choice. . . . The virtues of a market system cannot be preserved without exposing people to *some* market risks. But preserving these virtues does not require people bear whatever costs unregulated markets impose on them. Anderson, "How Should Egalitarians Cope," 257–258.

45 The inequalities at stake are not instituted for the sake of discriminating against less-preferred people, but to provide the price signals needed to direct people's choices in developing and exercising their talents in ways that are valued by others. Since such direction is inherent in the ideal of society as a system of cooperation among equals, it is hardly morally arbitrary, even if it results in distributive patterns that track morally arbitrary of birth to some degree. . . . The value of distributions is merely derivative of the value of social relationships, and tied to the right rather than the good. Anderson, "How Should Egalitarians Cope," 260–261.

46 Outcomes are the joint product of inner merit and extreme factors. Market choices are risky, strategic choices, the outcomes of which depend on the choices of other participants and on how well they anticipate the strategic choices of others. The choices that any individual makes in such market games are at best-educated guesses. There is no determinate point at which the calculated guess turns into the merely lucky guess, no way to divide the gains from an instance of good option luck into the component that can be credited to factors reasonably expected to be controlled or anticipated by the individual, and the component that can be credited to mere luck. Anderson, "How Should Egalitarians Cope," 248.

47 I prefer to base [the legitimacy of distributive arrangements] on the ground that they secure everyone's entitlements to the material conditions of their freedom and equality on a basis of reciprocity, with everyone interacting with each other on terms all can accept. Anderson, "Egalitarian Toolbox," 253–254.

48 To be capable of functioning as a human being requires effective access to the means of sustaining one' biological existence. . . not effective access to equal levels of functioning but effective access to levels sufficient to stand as an equal in society. Anderson, "What Is the Point," 318. People need a level of income sufficient to secure dignity in appearance. The minimal income needed to avoid personal subjection and enable effective participation as an equal in society thus sets an egalitarian floor on acceptable income variation. This floor is also related to the general level of consumption in society. The higher the general level of consumption, the more is needed by any particular individual to sustain a dignified appearance. Anderson, "How Should Egalitarians Cope," 266.

49 Even among wage workers, most of the differences are due to the fact that society has invested far more in developing some people's talents than others and that it puts very unequal amounts of capital at the disposal of each worker. Productivity attached mainly to work roles, not to individuals. Democratic equality deals with these facts by stressing the importance of educating the less advantaged and by offering firms incentives to increase the production of low-wage workers through capital investment. Anderson, "What Is the Point," 325–326.

50 I shall now argue that the triumph of the capitalist ethic of debt over the aristocratic and Christian ethics greatly advanced freedom and equality. . . . By freedom, I mean personal independence: freedom from bondage, from others' dominion. This was the view of freedom held by the classical economists. . . . The ability of ordinary people to obtain credit with dignity reflects a larger transformation in the moral economy of social status made possible by capitalism. . . . By contrast, exchange on the basis of mutual self-interest can preserve the independence and dignity of both parties. Capitalism, by enabling ordinary people to make a living without depending on noblesse oblige, thereby transformed the moral economy of social standing to a more egalitarian and potentially universalizable footing. State-imposed limitations on contracts restrict the freedom of the contracting parties to trade among one thing for another. Setting aside monopolies, externalities and information asymmetries, such limitations cannot be Pareto efficient. Anderson, "Ethical Assumptions," 348, 350–352, 355. Commercial republicanism secures widespread personal independence through a property regime that supports self-employment. This requires free markets in consumer goods and land, because state-granted monopolies and privileges, and property rules such as entail and primogeniture, concentrate the

means of production in a few hands and thereby force the rest into dependency. Elizabeth Anderson, “Equality and Freedom,” 7.

51 The conception of society as a system of cooperation provides a safety net through which even the imprudent are never forced to fall. It provides that no role in the productive system shall be assigned such inadequate benefits that, given the risks and requirements of the job, people could be deprived of the social conditions of their freedom because they fulfilled its requirements. . . . One mechanism for achieving a decent minimum would be a minimum wage. . . . Benefits could also be attached to work by other means, such as socially provided disability and old age pensions schemes, and tax credits for earned income. Anderson, “What Is the Point,” 325. When everyone shares an interest in some people making risky choices—when in effect, society has commissioned them to be farmers, miners, mothers, and so forth—it is unfair to disavow any share in the costs associated with commissioning people to take up these roles. To do so is effectively to discard people after using them. Everyone shares an interest in being insured against exposure to excess market risk. Anderson, “How Should Egalitarians Cope,” 257. Moreover, it is often better for all if institutions are required to internalize the cost of market risks. When employers rather than workers must shoulder the costs of workplace accidents, employers have an incentive to engineer their operations with due regard for the health and safety of employees. Anderson, “How Should Egalitarians Cope,” 256.

52 Principles of justice. . . . First, identify certain goods to which all citizens must have effective access over the course of their lives. . . guarantee[d] without resorting to paternalism. Anderson, “What Is the Point,” 314. *Democratic equality*, contrasts luck with security. On this view, unlucky distributions are unjust insofar as they disrupt egalitarian levels of security to which individuals are entitled because they need them to stand in relation of equality with others. . . . Democratic equality allows market exchanges to determine outcomes, subject to egalitarian constraints. Egalitarian social insurance sets people’s security levels so as to realize a society of equals. Democratic equality allows market exchanges to determine outcomes, subject to egalitarian constraints. Egalitarian social insurance sets people’s security levels so as to realize a society of equals. Anderson, “How Should Egalitarians Cope,” 240, 242.

53 Contractualism offers one way to justify these constraints. . . . Individuals are averse to suffering. This justifies a basic safety net. Individuals are also averse to experiencing substantial losses from their current condition, and are willing to give up chances of moving higher in the income distribution to insure against this event. This justifies middle-range constraints. If we assume, less plausibly, that individuals are willing to give up any chance of advancing up higher in order to maximize their minimum prospects, we can justify strong constraints at the top, such as Rawls’s difference principles. Anderson, “How Should Egalitarians Cope,” 262.

54 Private markets fail to cover numerous risks—for example disability insurance for those who work at dangerous occupations, disaster relief for those who live in areas prone to hurricanes and other natural disasters, insurance against failures of banks and private pension funds—at prices consistent with avoiding poverty. We share an interest in people choosing to mine or farm, to work in areas prone to storms and earthquakes, to deposit money in banks and provide for retirement in pensions. That is why social insurance and other forms of state-managed risk-pooling, such as federal emergency relief and pension insurance, have long been central planks of the egalitarian platform. Anderson, “How Should Egalitarians Cope,” 255.

55 Egalitarians insist that social insurance, along with other egalitarian range constraints such as the minimum wage, be regarded as *entitlements*–that is as private property rights. This is the key to how egalitarianism can be reconciled with a system of pure procedural justice in which market porcessess play a weighty role in determining distributive outcomes. Markets produce distributions subject to the constraints of proper rights. Social insurance and blocked exchanges simply define some of the constaints *of* (not “on”) private property. The resulting egalitarian system is what Rawls called a “property-owning democracy.” He contrasted a property-owning democracy with a welfare state, which conceived of social policies implemented not through property rights but through tax-and-transfer policies that lie *outside* the market system, and which were directed toward helping the unfortunate. . . .

That a property-owning democracy helps "those who lose out through accident or misfortune" is a *byproduct* of an entitlement system directed toward the *distinct* end of securing the material conditions of social equality for the members of society. Anderson, "How Should Egalitarians Cope," 268.

56 Egalitarians support distributive constraints that prevent the conversion of wealth inequality into an unjust social hierarchy, and ensure that everyone in society has enough to stand in relation of equality to others. Anderson, "How Should Egalitarians Cope," 263.

57 This does not imply that democratic equality must be indifferent between, say, a progressive income tax and a flat tax with a high personal deduction. There are compelling reasons to prefer a progressive income tax, *independent* of its tendency to globally reduce distributive inequality. Instead of viewing the tax system as a tool for achieving an independently defined global pattern of just distribution, one can view the problem of just taxation as a matter of local justice. A reasonable principle of just taxation is that people should share roughly equal burdens for supporting state projects, where burdens are relative to people's overall prosperity. Bill Gates will never feel the difference between a 25% and a 35% marginal tax rate on income over $60,000, but the ordinary middle class will. Of course, the principle of equal burdens is not the only principle of taxation; incentive effects, administrative efficiency, and numerous other considerations must also be factored in. Anderson, "What Is the Point," 3.

58 It is true that one implication of democratic equality is that all citizens are entitled to a sufficient level of certain capabilities that they can escape oppression by others and function as equals in civil society. Although this is the core of the view, concerns about equality do not stop there. As I note on p. 326 of my article, the more wealth is effectively convertible into goods such as political influence, the more of an interest democratic equality has in reducing great wealth inequalities, say, through highly progressive taxation. Moreover, my discussion of the economy as a comprehensive system of joint production is intended to provide a way of viewing the contributions of low-wage workers that could in principle motivate redistributive policies that push equality beyond ensuring that all have a minimum income. I just doubt whether this way of viewing the matter would motivate equalization policies as ambitious as Rawls' difference principle. To put the matter more concretely: although there is a spectacular wealth difference between my family and Bill Gates' family, my family enjoys such a fully satisfactory level of prosperity that I think only considerations of envy could motivate resentment on my part of Gates' superior wealth. I see no morally compelling reason to worry about wealth disparities between the prosperous middle class and the super-rich, provided the super-rich don't use their wealth to undermine democracy—for example, by buying elections—or to oppress other people. Anderson, "What Is the Point," 2.

59 There are hierarchies of *esteem . . . power . . . standing,* whereby those at the top are empowered to make claims on others in their right, and to enjoy rights and privileges, those below are denied rights or granted an inferior set of rights and privilege. . . . Egalitarians aim to abolish such hierarchies and replace them with relations of equality. While some command hierarchies are necessary, for instance in organizing the military defense of a community, securing law and order, and many aspects of cooperative production. . . . The fundamental reason for egalitarians to seek constraints at the top is that income and wealth do not buy only frivolities. They buy political power and influence, access to positions of command, and superior social standing. . . . Constraints at the top put everyone in the same boat, sharing common interests in social insurance. In addition, to the extent that wealth does influence politics, ensuring the fair value of equal political liberties requires policies aimed at limiting the top and not just raising the floor. Otherwise, the rich will capture the political agenda and secure public policies that specially cater to their interests, thereby converting democracy to plutocracy. Anderson, "How Should Egalitarians Cope," 264, 267.

60 The dominance of the rich in party-based mass democracies permits them to seize control of the bureaucratic apparatus of the state. He could have added that bureaucratic meritocracy also leads to crypto-plutocracy to the extent that the rich monopolize access to merit-creating training, which in most cases is higher education. Egalitarians need to counter this tendency by providing decent educational opportunities to disadvantaged groups of all kinds. Anderson, "Egalitarian Toolbox," 157.

The following notes are excerpted from Pope Francis, *Laudato Si'*, Encyclical letter on care for our common home, June 18, 2015.

A) 35 Today, however, we have to realize that a true ecological approach *always* becomes a social approach; it must integrate questions of justice in debates on the environment, so as to hear *both the cry of the earth and the cry of the poor*. 148 The gravity of the ecological crisis demands that we all look to the common good, embarking on a path of dialogue which requires patience, self-discipline and generosity, always keeping in mind that "realities are greater than ideas." 134 An assessment of the environmental impact of business ventures and projects demands transparent political processes involving a free exchange of views. On the other hand, the forms of corruption which conceal the actual environmental impact of a given project, in exchange for favours, usually produce specious agreements which fail to inform adequately and to allow for full debate. 106 The protection of the environment is in fact "an integral part of the development process and cannot be considered in isolation from it."

B) 114 We urgently need a humanism capable of bringing together the different fields of knowledge, including economics, in the service of a more integral and integrating vision. Today, the analysis of environmental problems cannot be separated from the analysis of human, family, work-related and urban contexts, nor from how individuals relate to themselves, which leads in turn to how they relate to others and to the environment. There is an interrelation between ecosystems and between the various spheres of social interaction, demonstrating yet again that "the whole is greater than the part." 109 As life and the world are dynamic realities, so our care for the world must also be flexible and dynamic. Merely technical solutions run the risk of addressing symptoms and not the more serious underlying problems. There is a need to respect the rights of peoples and cultures, and to appreciate that the development of a social group presupposes an historical process which takes place within a cultural context and demands the constant and active involvement of local people *from within their proper culture*. Nor can the notion of the quality of life be imposed from without, for quality of life must be understood within the world of symbols and customs proper to each human group. 132 Because the enforcement of laws is at times inadequate due to corruption, public pressure has to be exerted in order to bring about decisive political action. Society, through non-governmental organizations and intermediate groups, must put pressure on governments to develop more rigorous regulations, procedures and controls. . . . Unless citizens control political power—national, regional and municipal—it will not be possible to control damage to the environment. Local legislation can be more effective, too, if agreements exist between neighbouring communities to support the same environmental policies.

C) 61 Each creature has its own purpose. None is superfluous. 70 The rich and the poor have equal dignity. 14 I will point to the intimate relationship between the poor and the fragility of the planet, the conviction that everything in the world is connected, the critique of new paradigms and forms of power derived from technology, the call to seek other ways of understanding the economy and progress, the value proper to each creature, the human meaning of ecology, the need for forthright and honest debate, the serious responsibility of international and local policy, the throwaway culture and the proposal of a new lifestyle. These questions will not be dealt with once and for all, but reframed and enriched again and again. 15 The continued acceleration of changes affecting humanity and the planet is coupled today with a more intensified pace of life and work which might be called "rapidification." Although change is part of the working of complex systems, the speed with which human activity has developed contrasts with the naturally slow pace of biological evolution. Moreover, the goals of this rapid and constant change are not necessarily geared to the common good. Our goal is not to amass information or to satisfy curiosity, but rather to become painfully aware, to dare to turn what is happening to the world into our own personal suffering and thus to discover what each of us can do about it. 136 We know that water is a scarce and indispensable resource and a fundamental right which conditions the exercise of other human rights. This indisputable fact overrides any other assessment of environmental impact on a region. . . . The Rio Declaration of 1992 states that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a pretext for postponing cost-effective measures" which prevent environmental degradation. This precautionary principle makes it possible to protect those who are most vulnerable and whose ability to defend their interests and to assemble incontrovertible evidence is limited.

D) 12 We need a conversation which includes everyone, since the environmental challenge we are undergoing, and its human roots, concerns and affects us all. The worldwide ecological movement has already made considerable progress and led to the establishment of numerous organizations committed to raising awareness of these challenges. 32 Furthermore, when media and the digital world become omnipresent, their influence can stop people from learning how to live wisely, to think deeply and to love generously. In this context, the great sages of the past run the risk of going unheard amid the noise and distractions of an information overload. 33 Today's media do enable us to communicate and to share our knowledge and affections. Yet at times they also shield us from direct contact with the pain, the fears and the joys of others and the complexity of their personal experiences. For this reason, we should be concerned that, alongside the exciting possibilities offered by these media, a deep and melancholic dissatisfaction with interpersonal relations, or a harmful sense of isolation, can also arise.

E) 168 Around these community actions, relationships develop or are recovered and a new social fabric emerges. Thus, a community can break out of the indifference induced by consumerism. These actions cultivate a shared identity, with a story which can be remembered and handed on. In this way, the world, and the quality of life of the poorest, are cared for, with a sense of solidarity which is at the same time aware that we live in a common home.

F) 69 The Christian tradition has never recognized the right to private property as absolute or inviolable, and has stressed the social purpose of all forms of private property. . . . The Church does indeed defend the legitimate right to private property, but she also teaches no less clearly that there is always a social mortgage on all private property, in order that goods may serve the general purpose. 38 The land of the southern poor is rich and mostly unpolluted, yet access to ownership of goods and resources for meeting vital needs is inhibited by a system of commercial relations and ownership which is structurally perverse. The developed countries ought to help pay this debt by significantly limiting their consumption of non-renewable energy and by assisting poorer countries to support policies and programmes of sustainable development. The poorest areas and countries are less capable of adopting new models for reducing environmental impact because they lack the wherewithal to develop the necessary processes and to cover their costs. We must continue to be aware that, regarding climate change, there are *differentiated responsibilities*.

G) 106 The time has come to pay renewed attention to reality and the limits it imposes; this in turn is the condition for a more sound and fruitful development of individuals and society. We urgently need a humanism capable of bringing together the different fields of knowledge, including economics, in the service of a more integral and integrating vision. Today, the analysis of environmental problems cannot be separated from the analysis of human, family, work-related and urban contexts, nor from how individuals relate to themselves, which leads in turn to how they relate to others and to the environment. 131 In some places, cooperatives are being developed to exploit renewable sources of energy which ensure local self-sufficiency and even the sale of surplus energy. This simple example shows that, while the existing world order proves powerless to assume its responsibilities, local individuals and groups can make a real difference. They are able to instill a greater sense of responsibility, a strong sense of community, a readiness to protect others, a spirit of creativity and a deep love for the land. They are also concerned about what they will eventually leave to their children and grandchildren. These values are deeply rooted in indigenous peoples. 87 Modernity has been marked by an excessive anthropocentrism which today, under another guise, continues to stand in the way of shared understanding and of any effort to strengthen social bonds. The time has come to pay renewed attention to reality and the limits it imposes; this in turn is the condition for a more sound and fruitful development of individuals and society. An inadequate presentation of Christian anthropology gave rise to a wrong understanding of the relationship between human beings and the world. Often, what was handed on was a Promethean vision of mastery over the world, which gave the impression that the protection of nature was something that only the faint-hearted cared about. Instead, our "dominion" over the universe should be understood more properly in the sense of responsible stewardship. Neglecting to monitor the harm done to nature and the environmental impact of our decisions is only the most striking sign of a disregard for the message contained in the structures of nature itself. When we fail to acknowledge as part of reality the worth of a poor person, a human embryo, a person with disabilities—to offer just a few examples—it becomes difficult to hear the cry of nature itself; everything is connected. 60 When nature is viewed solely as a source of profit and gain, this has serious consequences for society. This vision of "might is right" has engendered immense inequality, injustice and acts of violence against the majority of humanity, since resources end up in the hands of the first comer or the most powerful: the winner takes all. Completely at odds with this model are the ideals of harmony, justice, fraternity and peace.

H) 154 The existence of laws and regulations is insufficient in the long run to curb bad conduct, even when effective means of enforcement are present. If the laws are to bring about significant, long-lasting effects, the majority of the members of society must be adequately motivated to accept them, and personally transformed to respond. Only by cultivating sound virtues will people be able to make a selfless ecological commitment.

I) 92 Any approach to an integral ecology, which by definition does not exclude human beings, needs to take account of the value of labour. 95 The loss of jobs also has a negative impact on the economy "through the progressive erosion of social capital: the network of relationships of trust, dependability, and respect for rules, all of which are indispensable for any form of civil coexistence."

J) 74–75 Technoscience, when well directed, can produce important means of improving the quality of human life, from useful domestic appliances to great transportation systems, bridges, buildings and public spaces. It can also produce art and enable men and women immersed in the material world to "leap" into the world of beauty. 142 Put simply, it is a matter of redefining our notion of progress. A technological and economic development which does not leave in its wake a better world and an integrally higher quality of life cannot be considered progress. Frequently, in fact, people's quality of life actually diminishes—by the deterioration of the environment, the low quality of food or the depletion of resources—in the midst of economic growth. In this context, talk of sustainable growth usually becomes a way of distracting attention and offering excuses. It absorbs the language and values of ecology into the categories of finance and technocracy, and the social and environmental responsibility of businesses often gets reduced to a series of marketing and image-enhancing measures. 143 The mindset which leaves no room for sincere concern for the environment is the same mindset which lacks concern for the inclusion of the most vulnerable members of society. For "the current model, with its emphasis on success and self-reliance, does not appear to favour an investment in efforts to help the slow, the weak or the less talented to find opportunities in life." 20 Its worst impact will probably be felt by developing countries in coming decades. Many of the poor live in areas particularly affected by phenomena related to warming, and their means of subsistence are largely dependent on natural reserves and ecosystemic services such as agriculture, fishing and forestry. They have no other financial activities or resources which can enable them to adapt to climate change or to face natural disasters, and their access to social services and protection is very limited.

K) 98 If an artist cannot be stopped from using his or her creativity, neither should those who possess particular gifts for the advancement of science and technology be prevented from using their God-given talents for the service of others. We need constantly to rethink the goals, effects, overall context and ethical limits of this human activity, which is a form of power involving considerable risks.

L) 70 The rich and the poor have equal dignity.

M) 36 Inequity affects not only individuals but entire countries; it compels us to consider an ethics of international relations. A true "ecological debt" exists, particularly between the global north and south, connected to commercial imbalances with effects on the environment, and the disproportionate use of natural resources by certain countries over long periods of time. The export of raw materials

N) 116–117 Human ecology is inseparable from the notion of the common good, a central and unifying principle of social ethics. The common good is "the sum of those conditions of social life which allow social groups and their individual members relatively thorough and ready access to their own fulfilment." Underlying the principle of the common good is respect for the human person as such, endowed with basic and inalienable rights ordered to his or her integral development. It has also to do with the overall welfare of society and the development of a variety of intermediate groups, applying the principle of subsidiarity. 143 Let us keep in mind the principle of subsidiarity, which grants freedom to develop the capabilities present at every level of society, while also demanding a greater sense of responsibility for the common good from those who wield greater power. Today, it is the case that some economic sectors exercise more power than states themselves. But economics without politics cannot be justified, since this would make it impossible to favour other ways of handling the various aspects of the present crisis. 147 Any technical solution which science claims to offer will be powerless to solve the serious problems of our world if humanity loses its compass, if we lose sight of the great motivations which make it possible for us to live in harmony, to make sacrifices and to treat others well. 166 We must regain the conviction that we need one another, that we have a shared responsibility for others and the world, and that being good and decent are worth it.

O) 150 This paradigm leads people to believe that they are free as long as they have the supposed freedom to consume. But those really free are the minority who wield economic and financial power. Amid this confusion, postmodern humanity has not yet achieved a new self-awareness capable of offering guidance and direction, and this lack of identity is a source of anxiety. We have too many means and only a few insubstantial ends. 84 Yet we can once more broaden our vision. We have the freedom needed to limit and direct technology; we can put it at the service of another type of progress, one which is healthier, more human, more social, more integral. Liberation from the dominant technocratic paradigm does in fact happen sometimes, for example, when cooperatives of small producers adopt less polluting means of production, and opt for a non-consumerist model of life, recreation and community. Or when technology is directed primarily to resolving people's concrete problems, truly helping them live with more dignity and less suffering. Or indeed when the desire to create and contemplate beauty manages to overcome reductionism through a kind of salvation which occurs in beauty and in those who behold it. An authentic humanity, calling for a new synthesis, seems to dwell in the midst of our technological culture. 91 This same "use and throw away" logic generates so much waste, because of the disordered desire to consume more than what is really necessary. 74–75 Yet it must also be recognized that nuclear energy, biotechnology, information technology, knowledge of our DNA, and many other abilities which we have acquired, have given us tremendous power. More precisely, they have given those with the knowledge, and especially the economic resources to use them, an impressive dominance over the whole of humanity and the entire world. Never has humanity had such power over itself, yet nothing ensures that it will be used wisely, particularly when we consider how it is currently being used. . . . The fact is that "contemporary man has not been trained to use power well because our immense technological development has not been accompanied by a development in human responsibility, values and conscience.

P) 130 The limits which a healthy, mature and sovereign society must impose are those related to foresight and security, regulatory norms, timely enforcement, the elimination of corruption, effective responses to undesired side-effects of production processes, and appropriate intervention where potential or uncertain risks are involved. There is a growing jurisprudence dealing with the reduction of pollution by business activities. But political and institutional frameworks do not exist simply to avoid bad practice, but also to promote best practice, to stimulate creativity in seeking new solutions and to encourage individual or group initiatives. A politics concerned with immediate results, supported by consumerist sectors of the population, is driven to produce short-term growth. 121 An interdependent world not only makes us more conscious of the negative effects of certain lifestyles and models of production and consumption which affect us all; more importantly, it motivates us to ensure that solutions are proposed from a global perspective, and not simply to defend the interests of a few.

Q) 160 Isolated individuals can lose their ability and freedom to escape the utilitarian mindset, and end up prey to an unethical consumerism bereft of social or ecological awareness. Social problems must be addressed by community networks and not simply by the sum of individual good deeds.

R) 142 Halfway measures simply delay the inevitable disaster. Put simply, it is a matter of redefining our notion of progress. A technological and economic development which does not leave in its wake a better world and an integrally higher quality of life cannot be considered progress. Frequently, in fact, people's quality of life actually diminishes—by the deterioration of the environment, the low quality of food or the depletion of resources—in the midst of economic growth. In this context, talk of sustainable growth usually becomes a way of distracting attention and offering excuses. It absorbs the language and values of ecology into the categories of finance and technocracy, and the social and environmental responsibility of businesses often gets reduced to a series of marketing and image-enhancing measures.

AA) 92 When the culture itself is corrupt and objective truth and universally valid principles are no longer upheld, then laws can only be seen as arbitrary impositions or obstacles to be avoided. 117 Finally, the common good calls for social peace, the stability and security provided by a certain order which cannot be achieved without particular concern for distributive justice; whenever this is violated, violence always ensues. Society as a whole, and the state in particular, are obliged to defend and promote the common good. 34 The impact of present imbalances is also seen in the premature death of many of the poor, in conflicts sparked by the shortage of resources, and in any number of other problems which are insufficiently represented on global agendas. It needs to be said that, generally speaking, there is little in the way of clear awareness of problems which especially affect the excluded. Yet they are the majority of the planet's population, billions of people.

AB) 49 "Tilling" refers to cultivating, ploughing or working, while "keeping" means caring, protecting, overseeing and preserving. This implies a relationship of mutual responsibility between human beings and nature. Each community can take from the bounty of the earth whatever it needs for subsistence, but it also has the duty to protect the earth and to ensure its fruitfulness for coming generations. 87 When we fail to acknowledge as part of reality the worth of a poor person, a human embryo, a person with disabilities—to offer just a few examples—it becomes difficult to hear the cry of nature itself; everything is connected. Once the human being declares independence from reality and behaves with absolute dominion, the very foundations of our life begin to crumble. 88 This situation has led to a constant schizophrenia, wherein a technocracy which sees no intrinsic value in lesser beings coexists with the other extreme, which sees no special value in human beings. But one cannot prescind from humanity. There can be no renewal of our relationship with nature without a renewal of humanity itself. There can be no ecology without an adequate anthropology. When the human person is considered as simply one being among others, the product of chance or physical determinism, then "our overall sense of responsibility wanes."

AC) 120 Men and women of our postmodern world run the risk of rampant individualism, and many problems of society are connected with today's self-centred culture of instant gratification. 51 Man must therefore respect the particular goodness of every creature, to avoid any disordered use of things.

AD) 35 This is due partly to the fact that many professionals, opinion makers, communications media and centres of power, being located in affluent urban areas, are far removed from the poor, with little direct contact with their problems. They live and reason from the comfortable position of a high level of development and a quality of life well beyond the reach of the majority of the world's population. This lack of physical contact and encounter, encouraged at times by the disintegration of our cities, can lead to a numbing of conscience and to tendentious analyses which neglect parts of reality. At times this attitude exists side by side with a "green."

AE) 140 It is a matter of openness to different possibilities which do not involve stifling human creativity and its ideals of progress, but rather directing that energy along new channels.

AF) 79 Human beings and material objects no longer extend a friendly hand to one another; the relationship has become confrontational. This has made it easy to accept the idea of infinite or unlimited growth, which proves so attractive to economists, financiers and experts in technology. It is based on the lie that there is an infinite supply of the earth's goods, and this leads to the planet being squeezed dry beyond every limit. It is the false notion that "an infinite quantity of energy and resources are available, that it is possible to renew them quickly, and that the negative effects of the exploitation of the natural order can be easily absorbed."

AG) 32 The social dimensions of global change include the effects of technological innovations on employment, social exclusion, an inequitable distribution and consumption of energy and other services, social breakdown, increased violence and a rise in new forms of social aggression, drug trafficking, growing drug use by young people, and the loss of identity. These are signs that the growth of the past two centuries has not always led to an integral development and an improvement in the quality of life. Some of these signs are also symptomatic of real social decline, the silent rupture of the bonds of integration and social cohesion. 24 The earth's resources are also being plundered because of short-sighted approaches to the economy, commerce and production. 25–26 Human beings must intervene when a geosystem reaches a critical state. But nowadays, such intervention in nature has become more and more frequent. As a consequence, serious problems arise, leading to further interventions; human activity becomes ubiquitous, with all the risks which this entails. Often a vicious circle results, as human intervention to resolve a problem further aggravates the situation.

AH) 18 The climate is a common good, belonging to all and meant for all. At the global level, it is a complex system linked to many of the essential conditions for human life. A very solid scientific consensus indicates that we are presently witnessing a disturbing warming of the climatic system. In recent decades this warming has been accompanied by a constant rise in the sea level and, it would appear, by an increase of extreme weather events, even if a scientifically determinable cause cannot be assigned to each particular phenomenon. Humanity is called to recognize the need for changes of lifestyle, production and consumption, in order to combat this warming. 138 The financial bubble also tends to be a productive bubble. The problem of the real economy is not confronted with vigour, yet it is the real economy which makes diversification and improvement in production possible, helps companies to function well, and enables small and medium businesses to develop and create employment. Here too, it should always be kept in mind that "environmental protection cannot be assured solely on the basis of financial calculations of costs and benefits. The environment is one of those goods that cannot be adequately safeguarded or promoted by market forces." Once more, we need to reject a magical conception of the market, which would suggest that problems can be solved simply by an increase in the profits of companies or individuals. Is it realistic to hope that those who are obsessed with maximizing profits will stop to reflect on the environmental damage which they will leave behind for future generations? Where profits alone count, there can be no thinking about the rhythms of nature, its phases of decay and regeneration, or the complexity of ecosystems which may be gravely upset by human intervention. Moreover, biodiversity is considered at most a deposit of economic resources available for exploitation, with no serious thought for the real value of things, their significance for persons and cultures, or the concerns and needs of the poor. 140 Efforts to promote a sustainable use of natural resources are not a waste of money, but rather an investment capable of providing other economic benefits in the medium term. If we look at the larger picture, we can see that more diversified and innovative forms of production which impact less on the environment can prove very profitable.

AI) 21 There has been a tragic rise in the number of migrants seeking to flee from the growing poverty caused by environmental degradation. They are not recognized by international conventions as refugees; they bear the loss of the lives they have left behind, without enjoying any legal protection whatsoever. Sadly, there is widespread indifference to such suffering, which is even now taking place throughout our world. Our lack of response to these tragedies involving our brothers and sisters points to the loss of that sense of responsibility for our fellow men and women upon which all civil society is founded. 66 But we should be particularly indignant at the enormous inequalities in our midst, whereby we continue to tolerate some considering themselves more worthy than others. We fail to see that some are mired in desperate and degrading poverty, with no way out. 104 We are faced not with two separate crises, one environmental and the other social, but rather with one complex crisis which is both social and environmental. Strategies for a solution demand an integrated approach to combating poverty, restoring dignity to the excluded, and at the same time protecting nature.

AJ) 31 Human beings too are creatures of this world, enjoying a right to life and happiness, and endowed with unique dignity. So we cannot fail to consider the effects on people's lives of Environmental deterioration, current models of development and the throwaway culture.

113 Lack of housing is a grave problem in many parts of the world, both in rural areas and in large cities, since state budgets usually cover only a small portion of the demand. Not only the poor, but many other members of society as well, find it difficult to own a home. Having a home has much to do with a sense of personal dignity and the growth of families. This is a major issue for human ecology.

AK) 117 In the present condition of global society, where injustices abound and growing numbers of people are deprived of basic human rights and considered expendable, the principle of the common good immediately becomes, logically and inevitably, a summons to solidarity and a preferential option for the poorest of our brothers and sisters. This option entails recognizing the implications of the universal destination of the world's goods, but . . . it demands before all else an appreciation of the immense dignity of the poor. . . . We need only look around us to see that, today, this option is in fact an ethical imperative essential for effectively attaining the common good.

AL) 39 The establishment of a legal framework which can set clear boundaries and ensure the protection of ecosystems has become indispensable, otherwise the new power structures based on the techno-economic paradigm may overwhelm not only our politics but also freedom and justice.

AM) 40 It is remarkable how weak international political responses have been. The failure of global summits on the environment make it plain that our politics are subject to technology and finance. There are too many special interests, and economic interests easily end up trumping the common good and manipulating information so that their own plans will not be affected. . . . "The interests of economic groups which irrationally demolish sources of life should not prevail in dealing with natural resources." The alliance between the economy and technology ends up sidelining anything unrelated to its immediate interests. Consequently the most one can expect is superficial rhetoric, sporadic acts of philanthropy and perfunctory expressions of concern for the environment, whereas any genuine attempt by groups within society to introduce change is viewed as a nuisance based on romantic illusions or an obstacle to be circumvented. 133 Results take time and demand immediate outlays which may not produce tangible effects within any one government's term. That is why, in the absence of pressure from the public and from civic institutions, political authorities will always be reluctant to intervene, all the more when urgent needs must be met. To take up these responsibilities and the costs they entail, politicians will inevitably clash with the mindset of short-term gain and results which dominates present-day economics and politics. But if they are courageous, they will attest to their God-given dignity and leave behind a testimony of selfless responsibility. A healthy politics is sorely needed, capable of reforming and coordinating institutions, promoting best practices and overcoming undue pressure and bureaucratic inertia. It should be added, though, that even the best mechanisms can break down when there are no worthy goals and values, or a genuine and profound humanism to serve as the basis of a noble and generous society.

BA) 130-131 The myopia of power politics delays the inclusion of a far-sighted environmental agenda within the overall agenda of governments. Thus we forget that "time is greater than space," that we are always more effective when we generate processes rather than holding on to positions of power. True statecraft is manifest when, in difficult times, we uphold high principles and think of the long-term common good. Political powers do not find it easy to assume this duty in the work of nation-building. 100 It sometimes happens that complete information is not put on the table; a selection is made on the basis of particular interests, be they politico-economic or ideological. This makes it difficult to reach a balanced and prudent judgement on different questions, one which takes into account all the pertinent variables. Discussions are needed in which all those directly or indirectly affected (farmers, consumers, civil authorities, scientists, seed producers, people living near fumigated fields, and others) can make known their problems and concerns, and have access to adequate and reliable information in order to make decisions for the common good, present and future. This is a complex environmental issue; it calls for a comprehensive approach which would require, at the very least, greater efforts to finance various lines of independent, interdisciplinary research capable of shedding new light on the problem.

BB) 130 There are not just winners and losers among countries, but within poorer countries themselves. Hence different responsibilities need to be identified. Questions related to the environment and economic development can no longer be approached only from the standpoint of differences between countries; they also call for greater attention to policies on the national and local levels. 122 A global consensus is essential for confronting the deeper problems, which cannot be resolved by unilateral actions on the part of individual countries. Such a consensus could lead, for example, to planning a sustainable and diversified agriculture, developing renewable and less polluting forms of energy, encouraging a more efficient use of energy, promoting a better management of marine and forest resources, and ensuring universal access to drinking water. 131–132 The urgent challenge to protect our common home includes a concern to bring the whole human family together to seek a sustainable and integral development, for we know that things can change. . . . Humanity still has the ability to work together in building our common home. 165 We know that technology based on the use of highly polluting fossil fuels—especially coal, but also oil and, to a lesser degree, gas—needs to be progressively replaced without delay. Until greater progress is made in developing widely accessible sources of renewable energy, it is legitimate to choose the lesser of two evils or to find short-term solutions. But the international community has still not reached adequate agreements about the responsibility for paying the costs of this energy transition.

BC) 130 In response to electoral interests, governments are reluctant to upset the public with measures which could affect the level of consumption or create risks for foreign investment. The myopia of power politics delays the inclusion of a far-sighted environmental agenda within the overall agenda of governments.

BD) 134 Environmental impact assessment should not come after the drawing up of a business proposition or the proposal of a particular policy, plan or programme. It should be part of the process from the beginning, and be carried out in a way which is interdisciplinary, transparent and free of all economic or political pressure. It should be linked to a study of working conditions and possible effects on people's physical and mental health, on the local economy and on public safety. Economic returns can thus be forecast more realistically, taking into account potential scenarios and the eventual need for further investment to correct possible undesired effects. A consensus should always be reached between the different stakeholders, who can offer a variety of approaches, solutions and alternatives. The local population should have a special place at the table.

BE) 84 By learning to see and appreciate beauty, we learn to reject self-interested pragmatism. If someone has not learned to stop and admire something beautiful, we should not be surprised if he or she treats everything as an object to be used and abused without scruple. If we want to bring about deep change, we need to realize that certain mindsets really do influence our behavior. Our efforts at education will be inadequate and ineffectual unless we strive to promote a new way of thinking about human beings, life, society and our relationship with nature. Otherwise, the paradigm of consumerism will continue to advance, with the help of the media and the highly effective workings of the market. 153 An awareness of the gravity of today's cultural and ecological crisis must be translated into new habits. Many people know that our current progress and the mere amassing of things and pleasures are not enough to give meaning and joy to the human heart, yet they feel unable to give up what the market sets before them. . . . We are faced with an educational challenge. Environmental education has broadened its goals. Whereas in the beginning it was mainly centred on scientific information, consciousness-raising and the prevention of environmental risks, it tends now to include a critique of the "myths" of a modernity grounded in a utilitarian mindset (individualism, unlimited progress, competition, consumerism, the unregulated market). It seeks also to restore the various levels of ecological equilibrium, establishing harmony within ourselves, with others, with nature and other living creatures, and with God. Environmental education should facilitate making. 156 Political institutions and various other social groups are also entrusted with helping to raise people's awareness.

BF) 35 If we reflect on the proper relationship between human beings and the world around us, we see the need for a correct understanding of work; if we talk about the relationship between human beings and things, the question arises as to the meaning and purpose of all human activity. This has to do not only with manual or agricultural labour but with any activity involving a modification of existing reality, from producing a social report to the design of a technological development. Underlying every form of work is a concept of the relationship which we can and must have with what is other than ourselves.

BG) 82 Yet by itself the market cannot guarantee integral human development and social inclusion. At the same time, we have "a sort of 'superdevelopment' of a wasteful and consumerist kind which forms an unacceptable contrast with the ongoing situations of dehumanizing deprivation" while we are all too slow in developing economic institutions and social initiatives which can give the poor regular access to basic resources. We fail to see the deepest roots of our present failures, which have to do with the direction, goals, meaning and social implications of technological and economic growth. 96 Civil authorities have the right and duty to adopt clear and firm measures in support of small producers and differentiated production. To ensure economic freedom from which all can effectively benefit, restraints occasionally have to be imposed on those possessing greater resources and financial power. To claim economic freedom while real conditions bar many people from actual access to it, and while possibilities for employment continue to shrink, is to practice a doublespeak which brings politics into disrepute. 109–110 The disappearance of a culture can be just as serious, or even more serious, than the disappearance of a species of plant or animal. The imposition of a dominant lifestyle linked to a single form of production can be just as harmful as the altering of ecosystems.

BH) 94–95 Nonetheless, once our human capacity for contemplation and reverence is impaired, it becomes easy for the meaning of work to be misunderstood. 101 We need to remember that men and women have "the capacity to improve their lot, to further their moral growth and to develop their spiritual endowments." 102 Work should be the setting for this rich personal growth, where many aspects of life enter into play: creativity, planning for the future, developing our talents, living out our values, relating to others. . . . It follows that, in the reality of today's global society, it is essential that "we continue to prioritize the goal of access to steady employment for everyone" no matter the limited interests of business and dubious economic reasoning. The goal should not be that technological progress increasingly replace human work, for this would be detrimental to humanity. Work is a necessity, part of the meaning of life on this earth, a path to growth, human development and personal fulfilment. Helping the poor financially must always be a provisional solution in the face of pressing needs. The broader objective should always be to allow them a dignified life through work.

BI) 140–141 For example, a path of productive development, which is more creative and better directed, could correct the present disparity between excessive technological investment in consumption and insufficient investment in resolving urgent problems facing the human family. It could generate sensible and profitable ways of reusing, revamping and recycling, and it could also improve the energy efficiency of cities. Productive diversification offers the fullest possibilities to human ingenuity to create and innovate, while at the same time protecting the environment and creating more sources of employment. Such creativity would be a worthy expression of our most noble human qualities, for we would be striving intelligently, boldly and responsibly to promote a sustainable and equitable development within the context of a broader concept of quality of life. On the other hand, to find ever new ways of despoiling nature, purely for the sake of new consumer items and quick profit, would be, in human terms, less worthy and creative, and more superficial.

BJ) 127 Enforceable international agreements are urgently needed, since local authorities are not always capable of effective intervention. Relations between states must be respectful of each other's sovereignty, but must also lay down mutually agreed means of averting regional disasters which would eventually affect everyone. Global regulatory norms are needed to impose obligations and prevent unacceptable actions. 128 The same mindset which stands in the way of making radical decisions to reverse the trend of global warming also stands in the way of achieving the goal of eliminating poverty. A more responsible overall approach is needed to deal with both problems: the reduction of pollution and the development of poorer countries and regions. The twenty-first century, while maintaining systems of governance inherited from the past, is witnessing a weakening of the power of nation states, chiefly because the economic and financial sectors, being transnational, tend to prevail over the political. Given this situation, it is essential to devise stronger and more efficiently organized international institutions, with functionaries who are appointed fairly by agreement among national governments, and empowered to impose sanctions. 154 If the laws are to bring about significant, long-lasting effects, the majority of the members of society must be adequately motivated to accept them, and personally transformed to respond. Only by cultivating sound virtues will people be able to make a selfless ecological commitment.

BK) 35 "Every *campesino* has a natural right to possess a reasonable allotment of land where he can establish his home, work for subsistence of his family and a secure life. This right must be guaranteed so that its exercise is not illusory but real. That means that apart from the ownership of property, rural people must have access to means of technical education, credit, insurance, and markets." 92–93 Labourers and craftsmen thus "maintain the fabric of the world." Developing the created world in a prudent way is the best way of caring for it, as this means that we ourselves become the instrument.

BL) 95 In other words, "human costs always include economic costs, and economic dysfunctions always involve human costs". To stop investing in people, in order to gain greater short-term financial gain, is bad business for society.)

BM) 95 Helping the poor financially must always be a provisional solution in the face of pressing needs. The broader objective should always be to allow them a dignified life through work. 136 This precautionary principle makes it possible to protect those who are most vulnerable and whose ability to defend their interests and to assemble incontrovertible evidence is limited.

BN) 126-127 If stringent measures are taken now, some countries with scarce resources will require assistance in adapting to the effects already being produced, which affect their economies. In this context, there is a need for common and differentiated responsibilities. As the bishops of Bolivia have stated, "the countries which have benefited from a high degree of industrialization, at the cost of enormous emissions of greenhouse gases, have a greater responsibility for providing a solution to the problems they have caused. For poor countries, the priorities must be to eliminate extreme poverty and to promote the social development of their people. At the same time, they need to acknowledge the scandalous level of consumption in some privileged sectors of their population and to combat corruption more effectively. They are likewise bound to develop less polluting forms of energy production, but to do so they require the help of countries which have experienced great growth at the cost of the ongoing pollution of the planet.

BO) 131–132 Because the enforcement of laws is at times inadequate due to corruption, public pressure has to be exerted in order to bring about decisive political action. Society, through non-governmental organizations and intermediate groups, must put pressure on governments to develop more rigorous regulations, procedures and controls. Unless citizens control political power—national, regional and municipal—it will not be possible to control damage to the environment. Local legislation can be more effective, too, if agreements exist between neighbouring communities to support the same environmental policies.

APPENDIX II: CONCEPTUAL SPECIFICATION OF MARKET IMPERFECTIONS

LBNL MARKET BARRIERS TO ENERGY EFFICIENCY

Barriers[1]	**Market Failures**	**Transaction Cost**[2]	**Behavioral factors**[16]
Misplaced Incentives	Externalities	Sunk Costs[3]	Custom[17]
Agency[4]	Mispricing[20]	Lifetime[5]	Values[18] & Commitment[19]
Capital Illiquidity[8]	Public Goods[22]	Risk[6] & Uncertainty[7]	Social Group & Status[21]
Bundling	Basic Research[23]	Asymmetric Info.[9]	Psychological Prospect[24]
Multi-Attribute	Information	Imperfect Info.[10]	Ability to Process Info[27]
Gold Plating[11]	Appropriability[25]	Cost[12]	Bounded Rationality[26]
Inseparability[13]	Imperfect Competition/	Search[15]	
Regulation Price Distortion[14]	Market Power[28]	Bargaining Cost	
Chain of Barriers			
Disaggregated Mkt.[15]			

Source: William H. Golove and Joseph H. Eto, *Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency*, Report LBL-38059, Lawrence Berkeley Laboratory, 1996. Page numbers are in parentheses at the end of each note.

1) Six market barriers were initially identified: 1) misplaced incentives, 2) lack of access to financing, 3) flaws in market structure, 4) mispricing imposed by regulation, 5) decision influenced by custom, and 6) lack of information or misinformation. Subsequently a seventh barrier, referred to as "gold plating," was added to the taxonomy (9).

2) Neo-classical economics generally relies on the assumption of frictionless transactions in which no costs are associated with the transaction itself. In other words, the costs of such activities as collecting and analyzing information; negotiating with potential suppliers, partners, and customers; and assuming risk are assumed to be nonexistent or insignificant. This assumption has been increasingly challenged in recent years. The insights developed through these challenges represent an important new way to evaluate aspects of various market failures (especially those associated with imperfect information). Transaction cost economics examines the implications of evidence suggesting that transaction costs are not insignificant but, in fact, constitute a primary explanation for the particular form taken by many economic institutions and contractual relations (22).

3) Transaction cost economics also offers support for claims that the illiquidity of certain investments leads to higher interest rates being required by investors in those investments (23).

4) Misplaced, or split, incentives are transactions or exchanges where the economic benefits of energy conservation do not accrue to the person who is trying to conserve (9).

5) Thus, as the rated lifetime of equipment increases, the uncertainty and the value of future benefits will be discounted significantly. The irreversibility of most energy efficiency investments is said to increase the cost of such investments because secondary markets do not exist or are not well-developed for most types of efficient equipment. This argument contends that illiquidity results in an option value to delaying investment in energy efficiency, which multiplies the necessary return from such investments (16).

6) If a consumer wishes to purchase an energy-efficient piece of equipment, its efficiency should reduce the risk to the lender (by improving the borrower's net cash flow, one component of credit-worthiness) and should, but does not, reduce the interest rate, according to the proponents of the theory of market barriers (10). Potential investors, it is argued, will increase their discount rates to account for this uncertainty or risk because they are unable to diversify it away. The capital asset pricing model (CAPM) is invoked to make this point (16).

7) Perfect information includes knowledge of the future, including, for example, future energy prices. Because the future is unknowable, uncertainty and risk are imposed on many transactions. The extent to which these unresolvable uncertainties affect the value of energy efficiency is one of the central questions in the market barriers debate. Of course, inability to predict the future is not unique to energy service markets. What is unique is the inability to diversify the risks associated with future uncertainty to the same extent that is available in other markets (20).

8) In practice, we observe that some potential borrowers, for example low-income individuals and small business owners, are frequently unable to borrow at any price as the result of their economic status or "credit-worthiness." This lack of access to capital inhibits investments in energy efficiency by these classes of consumers (10).

9) Finally, Williamson (1985) argues that the key issue surrounding information is not its public goods character, but rather its asymmetric distribution combined with the tendency of those who have it to use it opportunistically (23).

10) Knowledge of current and future prices, technological options and developments, and all other factors that might influence the economics of a particular investment. Economists acknowledge that these conditions are frequently not and in some cases can never be met. A series of information market failures have been identified as inhibiting investments in energy efficiency: (1) the lack of information, (2) the cost of information, (3) the accuracy of information, and (4) the ability to use or act upon information (20).

11) The notion of "gold plating" emerged from research suggesting that energy efficiency is frequently coupled with other costly features and is not available separately (11).

12) Even when information is potentially available, it frequently is expensive to acquire, requiring time, money, or both (20).

13) Inseparability of features refers specifically to cases where availability is inhibited by technological limitations. There may be direct tradeoffs between energy efficiency and other

desirable features of a product. In contrast to gold plating where the consumer must purchase more features than are desired, the inseparability of features demands purchases of lower levels of features than desired (2).

14) The regulation barrier referred to mispricing energy forms (such as electricity and natural gas) whose price was set administratively by regulatory bodies (11).

15) On the cost-side of the equation, the critics contend that, among other things, information and search costs have typically been ignored or underestimated in engineering/economic analyses. Time and/or money may be spent: acquiring new information (search costs), installing new equipment, training operators and maintenance technicians, or supporting increased maintenance that may be associated with the energy efficient equipment (16). The class, itself, consists of a distribution of consumers: some could economically purchase additional efficiency, while others will find the new level of efficiency is not cost effective (13).

16) Discounted cash-flow, cost-benefit, and social welfare analyses use price as the complete measure of value although in very different ways; behavioral scientists, on the other hand, have argued that a number of "noneconomic" variables contribute significantly to consumer decision making (17).

17) [C]ustom and information have evolved significantly during the market barrier debate (11).

18) In the language of (economic) utility theory, the profitability of energy efficiency investments is but one attribute consumers evaluate in making the investment. The value placed on these other attributes may, in some cases, outweigh the importance of the economic return on investment (19).

19) [P]sychological considerations such as commitment and motivation play a key role in consumer decisions about energy efficiency investments (17).

20) Externalities refer to costs or benefits associated with a particular economic activity or transaction that do not accrue to the participants in the activity (18).

21) Other factors, such as membership in social groups, status considerations, and expressions of personal values play key roles in consumer decision making (17). In order for a market to function effectively, all parties to an exchange or transaction must have equal bargaining power. In the event of unequal bargaining positions, we would expect that self-interest would lead to the exploitation of bargaining advantages (19).

22) Public goods are said to represent a market failure. It has been generally acknowledged by economists and efficiency advocates that public good market failures affect the energy services market. (19) The creation of information is limited because information has public good qualities. That is, there may be limits to the creator's ability to capture the full benefits of the sale or transfer of information, in part because of the low cost of subsequent reproduction and distribution of the information, thus reducing the incentive to create information that might otherwise have significant value (20).

23) Investment in basic research is believed to be subject to this shortcoming; because the information created as a result of such research may not be protected by patent or other property right, the producer of the information may be unable to capture the value of his/her creation (19).

24) Important theoretical refinements to this concept, known as prospect theory, have been developed by Tversky and Kahneman (1981, 1986). This theory contends that individuals do not make decisions by maximizing prospective utility, but rather in terms of difference from an initial reference point. In addition, it is argued that individuals value equal gains and losses from this reference point differently, weighing losses more heavily than gains (21).

25) The information created by the adoption of a new technology by a given firm also has the characteristics of a public good. To the extent that this information is known by competitors, the risk associated with the subsequent adoption of this same technology may be reduced, yet the value inherent in this reduced risk cannot be captured by its creator (19).

26) This work is consistent with the notion of bounded rationality in economic theory. In contrast to the standard economic assumption that all decision makers are perfectly informed and have the absolute intention and ability to make decisions that maximize their own welfare, bounded rationality emphasizes limitations to rational decision making that are imposed by

constraints on a decision maker's attention, resources, and ability to process information. It assumes that economic actors intend to be rational, but are only able to exercise their rationality to a limited extent (21).

27) Finally, individuals and firms are limited in their ability to use—store, retrieve, and analyze—information. Given the quantity and complexity of information pertinent to energy efficiency investment decisions, this condition has received much consideration in the market barriers debate (20).

28) This barrier suggests that certain powerful firms may be able to inhibit the introduction by competitors of energy-efficient, cost-effective products (10).

RESOURCES FOR THE FUTURE MARKET AND BEHAVIORAL FAILURES RELEVANT TO ENERGY EFFICIENCY

Societal Failures	Structural Failures	Potential Behavioral Failures[11]
Energy Market Failures	Capital Market Failures	Prospect Theory[12]
Environmental Externalities[1]	Liquidity Constraints[5]	Bounded Rationality[13]
Energy Security	Information Problems[6]	Heuristic Decision Making[14]
Innovation Market Failures	Lack of Information[7]	Information[15]
Research & Development Spillovers[2]	Asymmetric Info.	
Learning-by-Doing Spillovers[3]	Adverse Selection[8]	
Learning-by-Using[4]	Principal-Agent Problems[9]	
	Average-Cost Electricity Pricing[10]	

Source: Kenneth Gillingham, Richard G. Newell, and Karen Palmer, *Energy Efficiency Economics and Policy* (Washington, DC: Resources for the Future, 2009). Page numbers are in parentheses at the end of each note.

1) Externalities: the common theme in energy market failures is that energy prices do not reflect the true marginal social cost of energy consumption, either through environmental externalities, average cost pricing, or national security (9).

2) R&D spillovers may lead to underinvestment in energy-efficient technology innovation due to the public good nature of knowledge, whereby individual firms are unable to fully capture the benefits from their innovation efforts, which instead accrue partly to other firms and consumers (11).

3) Learning-by-doing (LBD) refers to the empirical observation that as cumulative production of new technologies increases, the cost of production tends to decline as the firm learns from experience how to reduce its costs (Arrow 1962). LBD may be associated with a market failure if the learning creates knowledge that spills over to other firms in the industry, lowering the costs for others without compensation.

4) Positive externalities associated with learning-by-using can exist where the adopter of a new energy-efficient product creates knowledge about the product through its use, and others freely benefit from the information generated about the existence, characteristics, and performance of the product (12).

5) Capital: Some purchasers of equipment may choose the less energy-efficient product due to lack of access to credit, resulting in underinvestment in energy efficiency and reflected in an implicit discount rate that is above typical market levels (13).

6) Information: Specific information problems cited include consumers' lack of information about the availability of and savings from energy-efficient products, asymmetric information, principal-agent or split-incentive problems, and externalities associated with learning-by-using (11).

7) Lack of information and asymmetric information are often given as reasons why consumers systematically underinvest in energy efficiency. The idea is that consumers often lack sufficient information about the difference in future operating costs between more-efficient and less-efficient goods necessary to make proper investment decisions (11).

8) Asymmetric information, where one party involved in a transaction has more information than another, may lead to adverse selection (11).

9) Agency: The principal-agent or split-incentive problem describes a situation where one party (the agent), such as a builder or landlord, decides the level of energy efficiency in a building, while a second party (the principal), such as the purchaser or tenant, pays the energy bills. When the principal has incomplete information about the energy efficiency of the building, the first party may not be able to recoup the costs of energy efficiency investments in the purchase price or rent charged for the building. The agent will then underinvest in energy efficiency relative to the social optimum, creating a market failure (12).

10) Prices faced by consumers in electricity markets also may not reflect marginal social costs due to the common use of average-cost pricing under utility regulation. Average-cost pricing could lead to under- or overuse of electricity relative to the economic optimum (10).

11) Systematic biases in consumer decision making that lead to underinvestment in energy efficiency relative to the cost-minimizing level are also often included among market barriers. (8); the behavioral economics literature has drawn attention to several systematic biases in consumer decision making that may be relevant to decisions regarding investment in energy efficiency. Similar insights can be gained from the literature on energy decision making in psychology and sociology. The evidence that consumer decisions are not always perfectly rational is quite strong, beginning with Tversky and Kahneman's research indicating that both sophisticated and naïve respondents will consistently violate axioms of rational choice in certain situations (15).

12) The welfare change from gains and losses is evaluated with respect to a reference point, usually the status quo. In addition, consumers are risk averse with respect to gains and risk seeking with respect to losses, so that the welfare change is much greater from a loss than from an expected gain of the same magnitude (Kahneman and Tversky 1979). This can lead to loss aversion, anchoring, status quo bias, and other anomalous behavior (16).

13) Bounded rationality suggests that consumers are rational, but face cognitive constraints in processing information that lead to deviation from rationality in certain circumstances (16); assessing the future savings requires forming expectations of future energy prices, changes in other operating costs related to the energy use (e.g., pollution charges), intensity of use of the product, and equipment lifetime. Comparing these expected future cash flows to the initial cost requires discounting the future cash flows to present values (3).

14) Heuristic decision making is related closely to bounded rationality and encompasses a variety of decision strategies that differ in some critical way from conventional utility maximization in order to reduce the cognitive burden of decision making. Tversky (1972) develops the theory of "elimination-by-aspects," wherein consumers use a sequential decision-making process where they first narrow their full choice set to a smaller set by eliminating products that do not have some desired feature or aspect (e.g., cost above a certain level), and then they optimize among the smaller choice set, possibly after eliminating further products (16). For example, for decisions regarding energy-efficient investments consumers tend to use a simple payback measure where the total investment cost is divided by the future savings calculated by using the energy price today, rather than the price at the time of the savings—effectively ignoring future increases in real fuel prices (17). The salience effect may influence energy efficiency decisions, potentially contributing to an overemphasis on the initial cost of an energy-efficient purchase, leading to an underinvestment in energy efficiency. This may be related to evidence suggesting that decision makers are more sensitive to up-front investment costs than energy-operating

costs, although this evidence may also be the result of inappropriate measures of expectations of future energy use and prices (17).

15) Alternatively, information problems may occur when there are behavioral failures, so that consumers are not appropriately taking future reductions in energy costs into account in making present investments in energy efficiency (12).

BARRIERS TO INDUSTRIAL ENERGY EFFICIENCY

Schools of Thought	Orthodox Economics Economics of What?	Agency Theory & Economics Information	Transaction Cost Economics	Behavioral
Imperfections	Risk[1]	Split Incentives[3]	Adverse Selection[6]	Inertia/ Status Quo Bias[9]
	Access to Capital[2]	Imperfect[4]		Bounded
	Routine[10]	Asymmetric Information[5] Hidden Costs[7]		Rationality[8]

Sorrell, Steve, Alexandra Mallett, and Sheridan Nye, *Barriers to Industrial Energy Efficiency, A Literature Review*, Working Paper, United Nations Industrial Development Organization, 2011, Figure 3.1 and Section 3.

1) Risk: The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because energy efficiency investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourages short time horizons.

2) Access to capital: If an organization has insufficient capital through internal funds, and has difficulty raising additional funds through borrowing or share issues, energy efficient investments may be prevented from going ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules and the short-term incentives of energy management staff.

3) Split incentives: Energy efficiency opportunities are likely to be foregone if actors cannot appropriate the benefits of the investment. Wide applicability. . . Landlord-tenant problems may arise in the industrial, public, and commercial sectors through the leasing of buildings and office space. The purchaser may have a strong incentive to minimize capital costs, but may not be accountable for running costs. . . . Maintenance staff may have a strong incentive to minimize capital costs and/or to get failed equipment working again as soon as possible, but may have no incentive to minimize running costs. If individual departments within an organization are not accountable for their energy use they will have no incentive to improve energy efficiency.

4) Imperfect information: Lack of information on energy efficiency opportunities may lead to cost-effective opportunities being missed. In some cases, imperfect information may lead to inefficient products driving efficient products out of the market. Information on: the level and pattern of current energy consumption and comparison with relevant benchmarks; specific opportunities, such as the retrofit of thermal insulation; and the energy consumption of new and refurbished buildings, process plant and purchased equipment, allowing choice between efficient and inefficient options.

5) Asymmetric information exists where the supplier of a good or service holds relevant information, but is unable or unwilling to transfer this information to prospective buyers.

6) Asymmetric information may lead to the adverse selection of energy inefficient goods.

7) Hidden costs: Engineering-economic analyses may fail to account for either the reduction in utility associated with energy efficient technologies, or the additional costs associated with them. As a consequence, the studies may overestimate energy efficiency potential. Examples of hidden costs include overhead costs for management, disruptions to production, staff replacement and training, and the costs associated with gathering, analyzing, and applying information.

General overhead costs of energy management: employing specialist people (e.g., energy manager); energy information systems (including: gathering of energy consumption data; maintaining sub metering systems; analyzing data and correcting for influencing factors; identifying faults; etc.); energy auditing.

Costs involved in individual technology decisions: i) identifying opportunities; ii) detailed investigation and design; iii) formal investment appraisal; formal procedures for seeking approval of capital expenditures; specification and tendering for capital works to manufacturers and contractors additional staff costs for maintenance; replacement, early retirement, or retraining of staff; disruptions and inconvenience.

Loss of utility associated with energy efficiency: problems with safety, noise, working conditions, service quality, etc. (e.g., lighting levels); extra maintenance, lower reliability.

8) Bounded rationality: Owing to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models. As a consequence, they may neglect opportunities for improving energy efficiency, even when given good information and appropriate incentive consumers do not attempt to maximize their utility or producers their profits.

9) Inertia and the status quo bias: Routines can be surprisingly persistent and entrenched. . . . This type of problem has been labeled *inertia* within the energy efficiency literature and identified as a relevant explanatory variable for the efficiency gap.

10) Routines as a response to bounded rationality the use of formal capital budgeting tools within investment decision making. Other types of rules and routines which may impact on energy efficiency include: operating procedures (such as leaving equipment running or on standby); safety and maintenance procedures; relationships with particular suppliers; design criteria; specification and procurement procedures; equipment replacement routines and so on.

MCKINSEY & COMPANY MARKET BARRIERS TO HOME ENERGY EFFICIENCY

KcKinsey Category	McKinsey Nature	McKinsey Description	Cluster
Behavioral	Awareness	Low priority, Preference for other attributes	CD, RLA
Availability	Availability	Restricted procurement, 1st cost focus	CD
Behavioral	Awareness	Shop for price and features	RD
Behavioral	Awareness	Limited understanding of use and savings	CEPB, EH, GB, RLA
Behavioral	Custom & Habit	Little attention at time of sale	NH
Behavioral	Custom & Habit	Underestimation of plug load	RD

(*Continued*)

(Continued)

KcKinsey Category	McKinsey Nature	McKinsey Description	Cluster
Behavioral	Custom & Habit	Aversion to change	CI,
Behavioral	Custom & Habit	CFLS perceived as inferior	RLA
Behavioral	Hurdle	Payback-Hurdle, 28% discount rate	CEPB
Behavioral	Hurdle	Payback-Hurdle, 40% discount rate	EH
Behavioral	Use	Improper use and maintenance	CEPB, EH, RD
Behavioral	Awareness	Not accountable for efficiency	CI
Availability	Capital	Competing use of capital	EH, GB, RLA, CI
Structural	Agency	Tenant pays, builder ignores	CEPB, EH, RD
Availability	Availability	Lack of contractors	EH
Availability	Availability	Lack of availability in area	NH
Availability	Availability	Lack of demand => lack of R&D	RD
Availability	Availability	Emergency replacement	RLA
Availability	Bundling	Efficiency bundled with other features	RLA
Structural	Owner Transfer	Lack of premium at time of sale	CD, NH, NPB, RLA
Structural	Owner Transfer	Limits payback to occupancy period	EH
Structural	Transaction	Lack of information	NPB
Structural	Transaction	Disruption during improvement process	EH
Structural	Transaction	Difficult to identify efficient devices	RD
Behavioral	Risk/Uncertainty	Business failure risk	CEPB
Behavioral	Risk/Uncertainty	Lack of reliability	CI
Structural	Transaction	Research, procurement and preparation	EH, GB, RLA

Source: McKinsey & Company, "Unlocking Energy Efficiency in the U.S. Economy." *McKinsey .com*, 2009; Tables 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, Exhibits 14, 15, 16, 19, 21, 24, 26, 27, 29, 30.

Chusters:

CD = Commercial Devices;

CEPB = Commercial Existing Private Buildings;

CI = Commercial Infrastructure;

EH = Existing Homes;

GB = Government Buildings;

NH = New Homes;

NPB = New Private Commercial Buildings;

RD = Residential Devices;

RLA = Residential Lighting and Appliances

McKinsey Categories Defined

Structural: These barriers arise when the market of environment makes investing in energy efficiency less possible or beneficial, preventing measures that would be NPV-positive from being attractive to an end-user:

Agency issues misaligned between economic actors, primarily between landlord and tenant making energy efficiency less possible or beneficial, preventing a measure that would be NPV. These barriers arise when the market or environment makes investing in (split incentives), in which energy bills and capital rights are

Ownership transfer issues, in which the current owner cannot capture the full duration of benefits, thus requiring assurance they can capture a portion of the future value upon transfer sufficient to justify upfront investment; this issue also affects builders and buyers. . . . Because developers do not receive the future energy savings from efficient buildings and are often unaware or uncertain of the market premium energy efficient buildings can command, developers have little financial incentive to invest in energy efficiency above the required minimum.

"Transaction" barriers, a set of hidden "costs" that are not generally monetizable, associated with energy efficiency investment; for example, the investment of time to research and implement a new measure. High transaction barriers arise as consumers incur significant time "costs" in researching, identifying, and procuring efficiency upgrades.

Pricing distortions, including regulatory barriers that prevent savings from materializing for users of energy-savings devices.

Behavioral: These barriers explain why an end-user who is structurally able to capture a financial benefit still decides not to:

Risk and uncertainty over the certainty and durability of measures and their savings generates an unfamiliar level of concern for the decision maker. Many operators are risk averse and put a premium on reliability; they may not be inclined to pursue energy efficiency activities for fear of disrupting essential services.

Lack of awareness, or low attention, on the part of end-users and decision makers in firms regarding details of current energy consumption patterns, potential savings, and measures to capture those savings. Homeowners typically do not understand their home energy consumption and are unaware of energy-saving measures.

Custom and habit, which can create inertia of "default choices" that must be overcome. Enduring lifestyle disruptions during the improvement process. End-users retain preconceived and often inaccurate ideas about differences in functionality that limit the acceptance of certain products.

Elevated hurdle rates, which translate into end-users seeking rapid pay back of investments - typically within 2 to 3 years. This expectation equates to a discount rate of 40 percent for investments in energy efficiency, inconsistent with the 7-percent discount rate they implicitly use when purchasing electricity (as embodied by the energy provider's cost of capital). It is beyond the scope of this report to evaluate the appropriate risk-adjusted hurdle rate for specific end-users, though it seems clear that the hurdle rates of energy delivery and energy efficiency are significantly different.

Availability: These barriers prevent adoption even for end-users who would choose to capture energy efficiency opportunities if they could:

Adverse bundling or "gold plating," situations in which the energy efficient characteristic of a measure is bundled with premium features, or is not available in devices with desirable features of higher priority, and is therefore not selected.

Capital constraints and access to capital, both access to credit for consumers and firms and (in industry and commerce) competition for resources internally within balance-sheet constraints. Energy efficiency projects may compete for capital with core business projects.

Product (and service) availability in the supply chain; energy efficient devices may not be widely stocked or available through customary purchasing channels, or skilled service personnel may not be available in a particular market.

Inconsistent quality of installation (sizing, sealing and charging, code compliance and enforcement) and improper use eliminates savings.

CONCEPTUAL SPECIFICATION FOR THE CLIMATE CHANGE ANALYSIS

EXTERNALITIES

Knowledge Externalities that are not captured by markets, a, *a*

- Research and Development b
- Importance of learning by searching c
- Deployment: Importance of learning by doing c

Economics of Scale/returns to scale d

Network effects d

MARKET STRUCTURE:

Cost Structures: Long investment cycles, increasing returns to scale, network effects e, j, *b*

Challenge of creating new markets:

Undifferentiated product i

Lack of competition hinders innovation *h*

Regulatory Risk g, j, *g*, *j*, *k*, *l*, *x*

- Carbon tax level and permanence g
- Fiscal policy *g*

ENDEMIC

Principle agent *w*

Shot-term view, g, i

Incomplete markets i

TRANSACTION COST

Uncertainty: as a cause of underinvestment *b*, *d*, *e*

High risk premia on new technologies

Information: Value of information *d*, *f*, *r*, *s*

Sunk costs and embedded infrastructure

POLITICAL POWER

Monopolistic structures and lack of competition *u*

INERTIA:

Cost of Inertia 1

POLICY

Lack of leadership, *x*

Statutory, *k*, *l*, *o*, *p*

Resources for The Future

Business Innovation Risk/Cost Effectiveness and Fiscal Barriers	Transaction Costs	Policy Obstacles – Regulatory/ Statutory barriers
Technical risk Volatile energy prices Market risk High up-front costs	Inadequate workforce/ infrastructure Misinformation Imperfect information Lack of specialized Inadequate validation Volatile energy prices	Unfavorable policy environment Unfavorable regulation Uncertain regulations Burdensome permitting Uncertain/unfavorable fiscal policy Misplaced incentives
Incumbent Support Industry structure Inadequate supply chain Monopoly power		

Sources: Lower case letters (a) from Raymond J. Kopp et al., *Assessing U.S. Climate Policy Options* (Washington, D.C.: Resources for the Future, November 2007). Italicized letters (*a*) are from Marylin A. Brown et al., *Carbon Lock-In: Barriers to Deploying Climate Mitigation Technologies* (Oak Ridge, TN: Oak Ridge National Laboratory, January 2008).

Oak Ridge: Causes of Carbon Lock-In

a) Public Goods: Similarly, rationales for public support of technology demonstration projects tend to point to the . . . inability of private firms to capture the rewards for designing and constructing first-of-a-kind facilities (120).

b) R&D tends to be underprovided in a competitive market because its benefits are often widely distributed and difficult to capture by individual firms. . . . Economics literature on R&D points to the difficulty firms face in capturing all the benefits from their investments in innovation, which tend to spill over to other technology producers and users (118–120). In addition, by virtue of its critical role in the higher education system, public R&D funding will continue to be important in training researchers and engineers with the skill necessary to work in either the public or private sector to produce GHG-reducing technology innovations (120). Generic public funding for research tends to receive widespread support based on significant positive spillovers that are often associated with the generation of new knowledge (136).

c) Another potential rationale involves spillover effects from the process of so-called "learning-by-doing"—a term that describes the tendency for production costs to fall as manufacturers gain production experience (136).

d) Network Effects: Network effects provide a motivation for deployment policies aimed at improving coordination and planning—and where appropriate, developing compatibility standards—in situations that involve interrelated technologies, particularly within large integrated systems (for example, energy productions, transmission, and distribution networks). Setting standards in a network context may reduce excess inertia (for example, the so-called chicken-and-egg problems with alternative fuel vehicles), while simultaneously reducing search and coordination costs, but standards can also reduce the diversity of technology options offered and may impede innovation over time (137).

e) Similarly, rationales for public support of technology demonstration projects tend to point to the large expense; high degree of technical, market and regulatory risk; and inability of private firms to capture the rewards for designing and constructing first-of-a-kind facilities (120).

f) Finally, incomplete insurance markets may provide a rationale for liability protection or other policies for certain technology options (for example, long-term CO_2 storage) (137).

g) Regulatory risk: Similarly, rationales for public support of technology demonstration projects tend to point to the. . . high degree of technical, market, and regulatory risk. The problem of private-sector under-investment in technology innovation may be exacerbated in the climate context where the energy assets involved are often very-long lives and where the incentives for bringing forward new technology rest heavily on domestic and international policies rather than natural market forces. Put another way, the development of climate-friendly technologies has little market value absent a sustained, credible government commitment to reducing GHG emissions (120).

h) The mismatch between near-term technology investment and long-term needs is likely to be even greater in situations where the magnitude of desired GHG reductions can be expected to increase over time. If more stringent emissions constraint will eventually be needed, society will benefit from near-term R&D to lower the cost of achieving those reductions in the future (p. 120).

i) Finally, incomplete insurance markets may provide a rationale for liability protection or other policies for certain technology options (for example, long-term CO_2 storage (137).

j) The problem of private-sector under-investment in technology innovation may be exacerbated in the climate context where the energy assets involved are often very-long lives and where the incentives for bringing forward new technology rest heavily on domestic and international policies rather than natural market forces. . . . Put another way, the development of climate-friendly technologies has little market value absent a sustained, credible government commitment to reducing GHG emissions (12).

Cost-Effectiveness Barriers

a) External Benefits and Costs: External benefits of GHG-reducing technologies that the owners of the technologies are unable to appropriate (e.g., GHG emission reductions from substitutes for high GWP gases and carbon sequestration).

b) External costs associated with technologies using fossil fuels (e.g., GHG emissions and health effects from small particles) making it difficult for higher priced, GHG-reducing technologies to compete.

c) High Costs: High up-front costs associated with the production and purchase of many low carbon technologies; high operations and maintenance costs typical of first-of-a-kind technologies; high cost of financing and limited access to credit especially by low-income households and small businesses.

d) Technical Risks: Risks associated with unproven technology when there is insufficient validation of technology performance. Confounded by high capital cost, high labor/operating cost, excessive downtime, lack of standardization, and lack of engineering, procurement, and construction capacity, all of which create an environment of uncertainty.

e) Market Risks: Low demand typical of emerging technologies including lack of long-term product purchase agreements; uncertainties associated with the cost of a new product vis-à-vis its competitors and the possibility that a superior product could emerge; rising prices for product inputs including energy feedstocks; lack of indemnification.

f) Lack of Specialized Knowledge: Inadequate workforce competence; cost of developing a knowledge base for available workforce; inadequate reference knowledge for decision makers.

Fiscal Barriers

g) Unfavorable Fiscal Policy: Distortionary tax subsidies that favor conventional energy sources and high levels of energy consumption; fiscal policies that slow the pace of capital stock turnover; state and local variability in fiscal policies such as tax incentives and property tax policies. Also includes various unfavorable tariffs set by the public sector and utilities (e.g., import tariffs for ethanol and standby charges for distributed generators) as well as unfavorable electricity pricing policies and rate recovery mechanisms.

h) Fiscal Uncertainty: Short-duration tax policies that lead to uncertain fiscal incentives, such as production tax credits; uncertain future costs for GHG emissions.

Regulatory Barriers

i) Unfavorable Regulatory Policies: Distortionary regulations that favor conventional energy sources and discourage technological innovation, including certain power plant regulations, rules impacting the use of combined heat and power, parts of the federal fuel economy standards for cars and trucks, and certain codes and standards regulating the buildings industry; burdensome and underdeveloped regulations and permitting processes; poor land use planning that promotes sprawl.

j) Regulatory Uncertainty: Uncertainty about future regulations of greenhouse gases; uncertainty about the disposal of spent nuclear fuels; uncertain siting regulations for off-shore wind; lack of codes and standards; uncertainty regarding possible future GHG regulations.

Statutory Barriers

k) Unfavorable Statutory Policies: Lack of modern and enforceable building codes; state laws that prevent energy-saving performance contracting.

l) Statutory Uncertainty: Uncertainty about future statutes including renewable and energy efficiency portfolio standards; unclear property rights relative to surface injection of CO_2, subsurface ownership of CO_2 and methane, and wind energy.

Intellectual Property Barriers

m) High Intellectual Property

n) Transaction Costs: High transaction costs for patent filing and enforcement, conflicting views of a patent's value, and systemic problems at the USPTO.

o) Anti-competitive Patent Practices Techniques such as patent warehousing, suppression, and blocking.

p) Weak International Patent Protection: Inconsistent or nonexistent patent protection in developing countries and emerging markets.

q) University, Industry, Government Perceptions: Conflicting goals of universities, national laboratories, and industry concerning CRADAs and technology commercialization.

Other Barriers

r) Incomplete and Imperfect Information: Lack of information about technology performance—especially trusted information; bundled benefits and decision-making complexities

s) High cost of gathering and processing information; misinformation and myths; lack of sociotechnical learning; and lack of stakeholders and constituents

t) Infrastructure Limitations: Inadequate critical infrastructure—including electric transmission capabilities and long-term nuclear fuel storage facilities; shortage of complementary technologies that encourage investment or broaden the market for GHG-reducing technologies; insufficient supply and distribution channels; lack of O&M facilities and other supply chain shortfalls

u) Industry Structure: Natural monopoly in utilities disenabling small-scale competition

v) Industry fragmentation slowing technological change, complicating coordination, and limiting investment capital

w) Misplaced Incentives: Misplaced incentives when the buyer/owner is not the consumer/user (e.g., landlords and tenants in the rental market and speculative construction in the buildings industry)—also known as the principal-agent problem

x) Policy Uncertainty: Uncertainty about future environmental and other policies; lack of leadership

EMPIRICAL EVIDENCE SUPPORTING THE MARKET IMPERFECTION AND POLICY ANALYSIS

This appendix presents sources and citations from the review of the empirical literatures that supports the analysis in Chapter 7. The tables from the text are repeated. We then present the sources in alphabetical order and assign each a number. The numbers from the tables correspond to the numbers in the source list. The numbering enables us to assign each source to a specific market imperfection or policy conclusion. Many of the sources are multifaceted, so they appear several times.

The citations are presented next. Lowercase letters refer to citations from the efficiency gap literature. Uppercase letters refer to citations from the climate change literature. Here we use the short form citation to identify the source in the alphabetical list. We have tried to extract quotes that bear directly on the area they are listed. The sources and citations are numbered sequentially to cover both the empirical analysis in this chapter and the empirical evidence that supports the analysis in Chapter 7. While there is some overlap in the lists, the majority of the citations are unique to one of the lists.

Recent Empirical Evidence Supporting the Market Imperfection and Policy Analysis

Schools of Thought/ Imperfection	**Efficiency**	**Climate**
Traditional		
Externalities		
Public Goods & Bads	28, 55, a, b	24, 132, 177, 197, ZL
Basic Research/Stock of Knowledge		46, 37, N
Network Effects	127, ak	82, 134, I, K
Learning-by-Doing & Using	47, i	134, 105, 120, 153, E
Localization		101, 153, 182, H
Industry Structure	122, 127, 163, 167	
Imperfect Competition		
Concentration	16, m	
Barriers to Entry		
Scale	39, r	151, G
Cost structure		44, 106, 134, I
Switching costs	165, t	
Technology	136, w	
R&D		90, 143, 15, E
Investment		
Marketing		
Bundling: Multi-attribute	162, 21, 116, z	
Cost-Price		
Limit impact of price	74, 116, ac	
Sluggish Demand/Fragmented Mkt.		82, 97, 110, W
Limited payback	74, 165, ae	

Behavioral	117, 133, 144, 149, 159, 173	
Motivation & Values	7, 6, h	39, ZM
Non-economic	4	
Influence & Commitment		
Custom	145, 146	
Social group & status	6, h	97, ZN
Perception	13, al	
Bounded Vision/Attention	1, 162, k	
Prospect/Risk Aversion	151, 165, l	
Calculation		77, 78 8, Z
Bounded rationality	10, 75, d, o	
Limited ability to process info	4, q	
Heuristic decision making	95, s	
Discounting difficulty	47, 95, 96, 113, 136, v	
Transaction Cost/Institutional		
Search and Information	88, 108	
Imperfect information	10, 100, n	19, 62, 90, U
Availability	10, 185, d	
Accuracy		
Search cost	41, 185, u	
Bargaining		
Risk & Uncertainty	32, 33, 165, t	42, 83, 103, 180, 188, R
Liability		
Enforcement		
Fuel Price		82, 134
Sunk costs		83
Hidden cost	185, ab	106
High Risk Premia		106, T
Incomplete Markets		82, 97, 179
Endemic Imperfections		
Asymmetric Info		
Agency	72, 163, 185, c, ad	83, 193, Q
Adverse selection	41, e	79, 44, X
Perverse incentives	167, f	
Lack of capital		
Political Power & Policy		
Monopoly/lack of competition		101, 155, 187, 188, ZB
Incumbent power		182, ZA
Institutional support	167, af	

(*Continued*)

(Continued)

Schools of Thought/ Imperfection	Efficiency	Climate
Inertia	136, ag	83, 1, 69, 106, M, V
Regulation		
Price	41, 88, 121, ah	
Aggregate, Avg.-cost	95, ai	
Allocating fuel price volatility		82, 98, 203, O
Permitting		
Lack of commitment	108, aj	83, 110, 156, 181

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Citations

a. Edelstein and Kilian, "Retail Energy Prices," 13. The cumulative effects on real consumption associated with energy price shocks are quantitatively important. We showed that the responses of real consumption aggregates are too large to reflect the effects of unanticipated change in discretionary income alone. Our analysis suggests that the excess response can be attributed to shifts in precautionary savings and to changes in the operating costs of energy-using durables.

b. Committee On Health, Environmental, and Other External Costs and Benefits Of Energy Production and Consumption, *Hidden Costs of Energy*, 1. Despite energy's many benefits, most of which are reflected in energy market prices, the production, distribution, and use of energy also cause negative effects. Beneficial or negative effects that are not reflected in energy market prices are termed "external effects" by economists. In the absence of government intervention, external effects associated with energy production and use are generally not taken into account in decision making. When prices do not adequately reflect them, the monetary value assigned to benefits or adverse effects (referred to as damages) are "hidden" in the sense that government and other decision makers, such as electric utility managers, may not recognize the full costs of their actions. When market failures like this occur, there may be a case for government interventions in the form of regulations, taxes, fees, tradable permits, or other instruments that will motivate such recognition.

c. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, 19. Asymmetric information exists where the supplier of a good or service holds relevant information, but is unable or unwilling to transfer this information to prospective buyers. The extent to which asymmetric information leads to market failure will depend upon the nature of the good or service. . . . In contrast to energy commodities, energy efficiency may only be considered a search good when the energy consumption of a product is clearly and unambiguously labelled and when the performance in use is insensitive to installation, operation, and maintenance conditions. But for many goods, the information on energy consumption may be missing, ambiguous, or hidden, and the search costs will be relatively high. In the absence of standardized performance measures or rating schemes, it may be difficult to compare the performance of competing products. Taken together, these features tend to make energy efficiency closer to a *credence good* and hence more subject to market failure. Thus, to the extent that energy supply and energy efficiency represent different means of delivering the same level of energy service, the latter is likely to be disadvantaged relative to the former. The result is likely to be overconsumption of energy and underconsumption of energy efficiency.

d. Alcott et al., *Beliefs and Consumer Choice*, 1. Results show that beliefs are both highly noisy, consistent with imperfect information and bounded by computational capacity, and systematically biased in manner symptomatic of "MPG illusion;" Alcott and Wozny, *Gasoline Prices*.

e. Davis, *Energy Efficient Investments*, 1. Extensive analysis of U.S. and global markets support the conclusion that this is an important impediment to greater energy efficiency of consumer durables. "The results show that, controlling for household income and other household characteristics, renters are significantly less likely to have energy efficient refrigerators, clothes washers and dishwashers."

f. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, 19. In some circumstances, asymmetric information in energy service markets may lead to the adverse selection of energy inefficient goods. Take housing as an example. In a perfect market, the resale value of a house would reflect the discounted value of energy efficiency investments. But asymmetric information at the point of sale tends to prevent this. Buyers have difficulty in recognizing the potential energy savings and rarely account for this when making a price offer. Estate agents have greater resources than buyers, but similarly neglect energy efficiency when valuing a house. Since the operating costs of a house affect the ability of a borrower to repay the mortgage, they should be reflected in mortgage qualifications. Again, they are not. In all cases, one party (e.g., the builder or the seller) may have the relevant information, but transaction costs impede the transfer of that information to the potential purchaser. The result may be to discourage house builders from constructing energy efficient houses, or to discourage homeowners from making energy efficiency improvements since they will not be able to capture the additional costs in the sale price.

g. Ozaki and Sevastyanova, "Going Hybrid."

h. Claudy and O'Dricoll, "Beyond Economics," 11. A growing body of literature around energy conservation contends that investment into energy efficiency measures is often motivated by "conviction" rather than "economics." Behavioral factors, including attitudes and values, explain a greater amount of variation in proenvironmental behavior and provide valuable insights for policy makers and analysts.

i. Desroches et al., *Incorporating Experience Curves*, 1. Costs and prices generally fall in relation to cumulative production, a phenomenon known as experience and modeled as a fairly robust empirical experience curve. . . . These experience curves . . . incorporated into recent energy conservation standards . . . impact on the national modeling can be significant, often increasing the net present value of potential standard levels. . . . These results imply that past energy conservation standards analyses may have undervalued the economic benefits of potential standard levels.

j. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, iii. If an organization has insufficient capital through internal funds, and has difficulty raising additional funds through borrowing or share issues, energy efficient investments may be prevented from going ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules, and the short-term incentives of energy management staff.

k. Alcott et al., *Beliefs and Consumer Choice*, 1. I provide evidence to suggest that at least some of this effect is because consumers' attention is malleable and non-durable. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, viii. Owing to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models. As a consequence, they may neglect opportunities for improving energy efficiency; even when given good information and appropriate incentive consumers do not attempt to maximize their utility or producers their profits.

l. Sardianou, "Barriers to Industrial Energy Efficiency," 1417. The decision-making process to invest in energy efficiency improvement, like other investments, is a function of the behavior of individual or of various actors within the industrial firm. In this context, managerial attitudes toward energy conservation are also important factors. . . . Energy efficiency measures are often overlooked by management because it is not a core business activity and it is thus not worth much attention.

m. Blumstein and Taylor, *Rethinking the Energy-Efficiency Gap*, 5. The existence of market power dampens the responsiveness of suppliers of goods or services to consumer demand, as actors in a monopolistic or oligopolistic setting can more or less set prices and quality attributes.

n. Atari et al., "Public Perceptions," 1. For a sample of 15 activities, participants underestimated energy use and savings by a factor of 2.8 on average, with small overestimates for lower-energy activities and large underestimates for high-energy activities.

o. Greene, German, and Delucchi, "Fuel Economy," 203. The uncertainty/loss aversion model of consumers' fuel economy decision making implies that consumers will undervalue expected future fuel savings to roughly the same degree as manufacturers' perception that consumers demand short payback periods.

p. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, iii. Lack of information on energy efficiency opportunities may lead to cost-effective opportunities being missed. In some cases, imperfect information may lead to inefficient products driving efficient products out of the market. Information on: the level and pattern of current energy consumption and comparison with relevant benchmarks; specific opportunities, such as the retrofit of thermal insulation; and the energy consumption of new and refurbished buildings, process plant and purchased equipment, allowing choice between efficient and inefficient options.

q. Atari et al., "Public Perceptions," p. 1. For a sample of 15 activities, participants underestimated energy use and savings by a factor of 2.8 on average, with small overestimates for lower-energy activities and large underestimates for high-energy activities.

r. Montalvo, "General Wisdom," S10. Due to the size of investment and longevity or production processes it is very likely that the diffusion of new processes will occur in an incremental way.

s. Ito, *Do Consumers Respond*, 1. Evidence from laboratory experiments suggests that consumers facing such price schedules may respond to average price as a heuristic. I empirically test this prediction using field data.

t. Sardianou, "Barriers to Industrial Energy Efficiency," 1419. Our empirical results also confirm that organizational constraints and human related factors can be thought of as barriers in incorporating the energy saving technology in incorporating the energy saving technology in the existing production process.

u. Sardianou, "Barriers to Industrial Energy Efficiency," 1419. Having limited information with regard to energy conservation opportunities and their profitability is considered an obstacle. . . . Other possible barriers include lack of documentation of energy data.

v. Kurani and Turrentine, *Automobile Buyer Decisions*, 1. One effect of limited knowledge is that when consumers buy a vehicle, they do not have the basic building blocks of knowledge to make an economically rational decision. When offered a choice to pay more for better fuel economy, most households were unable to estimate potential savings, particularly over periods of time greater than one month. In the absence of such calculations, many households were overly optimistic about potential fuel savings, wanting and thinking they could recover an investment of several thousand dollars in a couple of years.

w. Montalvo, "General Wisdom," S10. Finally, firms face the challenge of technological risk. The gains promised by new technologies have yet to materialize, a situation that contrasts strongly with the perceived reliability of the current, familiar operating process. In the literature on technology management it has been established that adoption or development of new production processes implies the capacity to integrate new knowledge and large organizational change.

x. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, iii. The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because energy efficiency investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourages short time horizons.

y. Montalvo, "General Wisdom," S10. Closely related to these technological opportunities are the firm and sector level capabilities to actually adopt new technologies. It has been reported that insufficient availability of expertise in clear production (eco-design), the current training and clean technology capacity building at the sector level, and the insufficient understanding and experience in cleaner production project development and implementation, play a role in the adoption of new cleaner production processes. These factors can be expected to become even more critical at the level of small- and medium-sized enterprises.

z. Gabaix and Laibson, *Shrouded Attributes*, 1. We show that information-shrouding flourishes even in highly competitive markets, even in markets with costless advertising, and even when the shrouding generation allocational inefficiencies.

aa. Sallee, *Rational Inattention*. The possibility of rational inattention has two key implications. First, if consumers rationally ignore energy efficiency, this could explain the energy paradox. In equilibrium, firms will underprovide energy efficiency if consumers ignore it. If true, this would qualitatively change the interpretation of empirical work on the energy paradox. Most empirical work tests for the rationality of consumer choice across goods that are actually sold in the market. If rational inattention leads to an inefficiency set of *product offerings* (emphasis added), consumers might choose rationally among goods in equilibrium but a paradox still exists. Second, if consumers are rationally inattentive to energy efficiency, this could provide direct justification for regulatory standards and "no tech policies, such as the Energy Star Label System."

ab. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, iii. Hidden Costs Engineering: economic analyses may fail to account for either the reduction in utility associated with energy efficient technologies, or the additional costs associated with them. As a consequence, the studies may overestimate energy efficiency potential. Examples of hidden costs include overhead costs for management, disruptions to production, staff replacement and training, and the costs associated with gathering, analyzing and applying information. General overhead costs of energy management: employing specialist people (e.g., energy manager); energy information systems (including: gathering of energy consumption data; maintaining sub metering systems; analyzing data and correcting for influencing factors; identifying faults; etc.); energy auditing; Costs involved in individual technology decisions: i) identifying opportunities; ii) detailed investigation and design; iii) formal investment appraisal; formal procedures for seeking approval of capital expenditures; specification and tendering for capital works to manufacturers and contractors additional staff costs for maintenance; replacement, early retirement, or retraining of staff; disruptions and inconvenience; Loss of utility associated with energy efficiency: problems with safety, noise, working conditions, service quality, etc. (e.g., lighting levels); extra maintenance, lower reliability.

ac. Li, von Haefen, and Timmins, "Fleet Fuel Economy." We are able to decompose the effects of gasoline prices on the evolution of the vehicle fleet into changes arising from the inflow of new vehicles and the outflow of used vehicles. We find that gasoline prices have statistically significant effects on both channels, but their combined effects result in only modest impacts on fleet fuel economy. The short-run and long-run elasticities of fleet fuel economy with respect to gasoline prices are estimated at 0.022 and 0.204 in 2005.

ad. Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles, National Research Council of the National Academies, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles* (The National Academies Press, Washington, D.C., 2010), 2. The [Medium and Heavy Duty] truck world is more complicated. There are literally thousands of different configurations of vehicles including bucket trucks, pickup trucks, garbage trucks, delivery vehicles, and long-haul trailers. Their duty cycles vary greatly. . . . The party responsible for the final truck configuration is often not well defined.

ae. Sardianou, "Barriers to Industrial Energy Efficiency," 1419. The lack of access to capital (76%) and the slow rate of return (74%) of energy savings investments are categorized as barriers.

af. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, iii. Routines as a response to bounded rationality the use of formal capital budgeting tools within investment decision making. Other types of rules and routines which may impact on energy efficiency include: operating procedures (such as leaving equipment running or on standby); safety and maintenance procedures; relationships with particular suppliers; design criteria; specification and procurement procedures; equipment replacement routines and so on.

ag. Montalvo, "General Wisdom," S11. Organization capabilities refer to the firm's endowments and capabilities to carry out innovation. . . . When the knowledge is not present in the firm adoption will depend on the firm's capacity to overcome skill lock-in, and to unlearn and acquire new skills. UNIDO, Inertia and the status quo bias: Routines can be surprisingly persistent and entrenched. . . . This type of problem has been labeled inertia within the energy efficiency literature and identified as a relevant explanatory variable for the efficiency gap.

ah. Sardianou, "Barriers to Industrial Energy Efficiency," 1419. Uncertainty about future energy prices (62%) is also characterized as a barrier [leading] to the postponement of energy efficiency measures.

ai. Ito, *Do Consumers Respond*, 1. I find strong evidence that consumers respond to average price rather than marginal or expected marginal price.

aj. Sorrell, Mallett, and Nye, *Barriers to Industrial Energy Efficiency*, 67. The government does not give financial incentives to improve energy efficiency, Lack of coordination between different government agencies, Lack of enforcement of government regulations, There is a lack of coordination between external organizations. Sardianou, "Barriers to Industrial Energy Efficiency," p. 1402. Bureaucratic procedure to get government financial support is a barrier to energy efficiency improvements for the majority (80%) of industries.

aj. Consumer Reports, "Auto Pulse #26: Fuel Economy," April 26, 2012, 8. This suggests that many consumers are misinformed about the program.

ak. Lutzenhiser, Loren, et al., *Market Structure and Energy Efficiency: The Case of New Commercial Buildings*, California Institute For Energy Efficiency, 2001 cited in Blumstein and Taylor, *Rethinking the Energy-Efficiency Gap*), viii. The commercial building "industry" is in fact a series of linked industries arrayed along a "value chain" or "value stream" where each loosely coupled link contributes value to a material building in process. Each link, while aware of the other links in the process, is a somewhat separate social world with its own logic, language, actors, interests, and regulatory demands. For the most part "upstream" actors constrain the choices and actions of "downstream" actors.

al. Jessoe, Katrina and David Rapson, 2013, *Knowledge Is (Less) Power: Experimental Evidence from Residential Energy Use*, February 19, 2001, 34. These results confirm the practical importance of one of economics' most ubiquitous assumptions—that decision makers have perfect information. Indeed, the absence of perfect information is likely to cause substantial efficiency losses both in this setting and others in which quantity is also infrequently or partially observed by decision makers.

CLIMATE CHANGE ANALYSIS

A Walz, Schleich, and Ragwitz, *Regulation, Innovation and Wind Power Technologies*, 16. Power prices, however, are not found to drive patent activity. Hence power prices alone would likely not be sufficient to spur innovation activities in wind and arguably also other, currently less cost-efficient renewable technologies.

B The stability and long term vision of policy target setting are important policy style variables, which contribute to the legitimacy of technology and provide guidance of search.

C Calel and Dechezloprete, "Environmental Policy," 173. More refined estimates that combine matching methods with different-in-difference provide evidence that the EU ETS has not impacted the direction of technological change. This finding appears to be robust to a number of stability and sensitivity checks. While we cannot completely rule out the possibility that the EU ETS has impacted only large companies for which suitable unregulated comparators cannot be found, our findings suggest that the EU ETS so far has had at best a very limited impact on low-carbon technological change.

E Massetti and Nicita, *Optional Climate Policy*, 17. We find that a [carbon] stabilization policy together with an R&D policy targeted at the only energy sector is significantly less costly than the stabilization policy alone. We find that energy R&D does not crowd-out non-energy R&D, and thanks to intersectoral spillovers, the policy induced increase in energy efficiency R&D spills over to the non-energy sector, contributing to knowledge accumulation and the reduction of knowledge externalities.

G Qui and Anadon, "The Price of Wind," 782. The size of the wind farm is another significant factor in all specifications . . . indicate that a doubling in wind farm size could lead to price reductions of about 8.9%.

H Qui and Anadon, "The Price of Wind," 782. Localization rate is a significant factor in all specifications . . . indicate that a doubling of localization rate was associated with reductions in wind electricity price ranging from 10.9% to 11.4%.

I de Cian and Massimo, "Mitigation Portfolio," p. 123. Uncertainty and irreversibility are two features of climate change that contribute to shape the decision-making process.

Technology cost uncertainty can depress the incentive to invest. The risk of underinvestment is even more severe considering that energy infrastructure has a slow turnover. Capital irreversibility and uncertainty heighten the risk of locking into existing fossil-fuel-based technologies. Additional investments are sunk costs that increase the opportunity cost of acting now. . . . The result is reinforced when uncertain costs have a large variance, showing that investments decrease with risk. Jamasb, Tooraj, and Jonathan Kohler, *Learning Curves for Energy Technology: A Critical Assessment*. Cambridge Working Paper 0752, University of Cambridge, October 2007, 8. R&D activity can be subject to three main types of market failure, namely indivisibility, uncertainty, and externalities.

K Gross et al., *On Picking Winners*, 18. In the energy sector, such "network externalities" rise for example in the physical structures of large scale high voltage alternating current (AC) power grids themselves (themselves a reminder of early energy planners' desire to locate power stations close to the source of coal) which now provides a cost advantage to large-scale centralized stations over distributed alternatives.

M Grimaud and Lafforgue, "Climate Change Mitigation Policies," 1, 20. The main results of the paper are the following: i) both a carbon tax and a green research subsidy contribute to climate change mitigation; ii) R&D subsidies have a large impact on the consumption, and then social welfare, as compared to the carbon tax alone; IV) those subsidies allow to spare the earlier generations who are, on the other hand, penalized by a carbon tax. . . . In a second-best world, a carbon tax used alone leads to a higher social cost (with respect to first-best) than a research policy alone.

N Jamasb and Kohler, *Learning Curves*, 9. Information technology and pharmaceuticals, for example, are both characterized by high degrees of innovation, with rapid technological change financed by private investment amounting typically to 10–20% of sector turnover. This is in dramatic contrast with power generation, where a small number of fundamental technologies have dominated for almost a century and private sector RD&D has fallen sharply with privatization of energy industries to the point where it is under 0.4% of turnover.

O Gross et al., *On Picking Winners*, 14. Capital intensive, zero fuel cost power stations like wind farms, need to cover their long run average costs—namely the cost of capital. They can neither actively affect/set marginal power prices nor respond to power price changes, except to curtail output, which does not save costs (as there are no fuel costs to save), but does lose revenue. However, carbon prices only affect the marginal price of fuel and power. We should therefore expect that an emissions trading scheme will encourage fuel switching from coal to gas, and efficiency first and renewable energy (or indeed nuclear) investment last. This is exactly what we have seen in reality.

Q Gross, Blyth, and Heponstall, "Risks, Revenues and Investment," 802. A range of factors that relate to the amount and quality of information about technology costs and risks available to policymakers and market participants are relevant when considering incentives and investment in new technologies: Policymakers may have relatively poor information about costs for emerging technologies. "Appraisal optimism" (where technology/project developers underestimate the cost of unproven technology/systems) is a common feature in the development of new technologies. When providing cost data to policymakers technology developers or equipment suppliers may also have incentives to up or play down costs and potential according to circumstances. Where new or unproven technologies are being utilized for the first time, information about costs may be limited for all concerned. . . . There may be an 'option value' to potential investors in waiting (delaying investment) where there is poor information and high levels of technology and market risk. The first conclusion is that policymaking in the energy area needs new tools of analysis that can deal with the market risks associated with policy design. . . . In particular, policymakers need to be mindful of the role of revenue risk as well as cost risk in the business case for investment.

R Fuss and Szolgayova, "Fuel Price and Technological Uncertainty," 2938. We find that the uncertainty associated with the technological progress of renewable energy technologies leads to a postponement of investment. Even the simultaneous inclusion of stochastic fossil fuel prices in the same model does not make renewable energy competitive compared to fossil-fuel-fired technology in the short run based on the data used. This implies that policymakers have to intervene if renewable energy is supposed to get diffused more quickly. Otherwise, old fossil-fuel-fired equipment will be refurbished or replaced by fossil-fuel-fired capacity again, which enforces the lock-in of the current system into unsustainable electricity generation.

T Gross, Blyth, and Heponstall, "Risks, Revenues and Investment," 802. The first conclusion is that policymaking in the energy area needs new tools of analysis that can deal with the market risks associated with policy design. . . . In particular, policymakers need to be mindful of the role of revenue risk as well as cost risk in the business case for investment.

U Horbach, "Determinants of Environmental Innovations," 172. Environmental management tools help to reduce the information deficits to detect cost savings (especially material and energy savings) that are an important driving force of environmental innovation.

V Weyant, "Beyond the Valley of Death," 677. The infrastructure for producing, distributing, and promoting the industries' current products requires large investments that have already been incurred.

W Jamasb and Kohler, *Learning Curves*. Thus, the "market pull" forces reach deep into the innovation chain. . . . This is in contrast with power generation, where a small number of fundamental and private sector RD&D has fallen sharply with privatization of energy industries. Technologies have dominated for almost a century and private RD&D has fallen sharply with privatization. . . . In turn, market pull measures are devised to promote technical change by creating demand and developing the market for new technologies.

X Weyant, "Beyond the Valley of Death," 675. The situation can develop from several different types of market failure, including poor or asymmetric information available to purchasers, limits on individuals' ability to make rational decisions because of time or skill constraints, principle agent incongruities . . . and lack of financing opportunities.

Z Greene, *How Consumers Value Fuel Economy*, 6. The rational economic consumer considers fuel saving over the full life of a vehicle, discounting future fuel savings to present value. This requires the consumer to know how long the vehicle will remain in operation; the distances to be traveled in each future year, the reduction in the rate of fuel consumptions, and the future price of fuel. . . . The consumer must also estimate the fuel economy that will be achieved in real world driving based on the official estimate. Finally, the consumer must know how to make a discounted present value calculation, or must know how to obtain one. . . . The utility-maximizing rational consumer has fixed preferences, possesses all complete and accurate information about all relevant alternatives, and has all the cognitive skills necessary to evaluate the alternatives. These are strict requirements indeed.

ZA Nicolli and Vona, "The Evolution of Renewable Energy Policy," 1. Our empirical results are consistent with predictions of political-economy models of environmental policies as lobbying, income, and, to a less extent, inequality have expected effects on policy. The brown lobbying power, proxied by entry barriers in the energy sector, has negative influence on the policy indicators even when taking into account endogeneity in its effect. The results are also robust to dynamic model specifications and to the exclusion of groups of countries

ZB Weyant, "Beyond the Valley of Death," 677. Further complicating matters, existing companies in energy-related industries—those that produce energy, those that manufacture the equipment that produces, converts, and uses energy, and those that distribute energy—can have substantial incentives to delay the introduction of new technologies. This can happen if their current technologies are more profitable than the new ones that might be (or have been) invented, or if they are in explicitly (oil and gas) or implicitly (electric generation equipment producers and automakers) oligopolisticly structured, or if they are imperfectly regulated (electric and gas utilities). The incentive arises partly because the infrastructure for producing, distributing, and promoting the industries' current products require large investments that have already been incurred.

ZC Horbach, "Determinants of Environmental Innovations," 172. An environmentally oriented research policy has not only to regard traditional instruments like the improvement of the technological capabilities of a firm but also the coordination with soft environmental policy instruments like the introduction of environmental management systems.

ZE Wilson et al., "Marginalizaton of End Use Technologies," 781. The institutions emphasized in our analytic framework are twofold: the propensity of entrepreneurs to invest in risky innovation activities with uncertain pay-offs; and shared expectations around an innovation's future trajectory. Other important and related institutions include law, markets, and public policy. Public resources are invested directly into specific innovation stages, or are used to leverage private sector resources through regulatory or market incentives structured by public policy. . . . New technologies successfully diffuse as a function of their relative advantage over incumbent technologies. For energy technologies, this can be measured by the difference in cost and performance of energy service provision in terms of quality, versatility, environmental impact, and so on. Many of these attributes of relative advantage can be shaped by public policy as well as the other elements of the innovation system.

ZF Walz, Schleich, and Ragwitz, *Regulation, Innovation and Wind Power Technologies*, 5. The specific advantage of feed-in tariffs is seen in lower transaction costs and reduced risk perception for investors and innovators, which are extremely important especially for new entrants and for financial institutions.

ZH Walz, Schleich, and Ragwitz, *Regulation, Innovation and Wind Power Technologies*, 16. Our econometric analyses also imply that the existence of targets for renewables/wind and a stable policy support environment are associated with higher patent activity.

ZL Maxim, "Sustainability Assessment," 284. Measuring the sustainability of the energy sector has evolved around three main dimensions: environmental, economic, and social.

ZM Croson and Treich, "Behavioral Environmental Economics," 336. This literature has often discussed how traditional policy instruments (like taxes), or traditional methods (like cost-benefit analysis), can be affected by behavioral concerns, including taxes crowding out public good contributions or the impact of hyperbolic discounting or reference-dependent preferences on environmental policy. This research which integrates human limitations into environmental economics is refreshing, and shows great promise. Scholars, policy makers and politicians have enthusiastically embraced this research. One reason may be the increasing awareness of environmental problems, and of the evident difficulty in solving these problems using traditional instruments. Another reason may be the low cost of many behavioral interventions. An additional, more concealed, reason may be a general distrust in the market system and classical economics by individuals in these positions.

ZO Cordes and Schwesinger, "Technological Diffusion," passim. Proposition 1. Preference acquisition processes based upon social learning can override a technology's relative cost and/or hedonistic disadvantages and therefore lead to its diffusion in a population of interacting adopters. . . . Proposition 2. If a dedicated cultural rolemodel takes effect in consumers' preference learning during certain critical time spans or "windows of opportunity", it can persistently promote the diffusion of a green technology. . . . Proposition 3. State regulation that temporarily creates a niche for a green technology by preventing competitive impacts of other technologies can help decrease its cost or hedonistic disadvantages by gaining adopters in the niche market. Subsequently, a technology can be able to diffuse further even after the removal of this kind of governmental protection. . . . Proposition 4. Environmental policy instruments that comprise the promotion of "green preferences" via social learning in combination with measures to lower relative cost disadvantages can be expected to be more efficient and effective as to the fostering of a green technology's diffusion in a population of interacting adopters.

ZP Spence et al., "Public Perceptions," 550. We show that, although cost is likely to be a significant reason for many people to take up DSM measures, those concerned about energy costs are actually less likely to accept DSM. Notably, individuals concerned about climate change are more likely to be accepting. A significant proportion of people, particularly those concerned about affordability, indicated unwillingness or concerns about sharing energy data, a necessity for many forms of DSM. We conclude substantial public engagement and further policy development is required for widespread DSM implementation.

ZQ Zinaman, pp. 113. . .125, Rapid cost reductions—for example, of photovoltaic modules—have changed the economic landscape for what is feasible. Yet established asset bases, and their supporting business models and regulatory frameworks, still retain significant inertia in most power systems. These longstanding financial and institutional ''legacy'' arrangements promote incremental change. . . . Whether the trends outlined in Section II are ''headwinds'' or ''tailwinds'' will depend on the orientation set by decision makers for their power systems. Policymakers and regulators can choose to let these external forces determine how power systems unfold, or they can promote policies and build regulatory and finance frameworks that drive the transformation toward a desired vision. As a final organizing principle, early and frequent stakeholder engagement will encourage the emergence of modern power systems that accommodate a broad set of interests and best serve citizens and energy customers.

ZR Zinaman et al., "Power Systems of the Future," passim. Trends: Ten Trends: Renewable energy cost reductions, Innovations in data, intelligence, and system optimization, Energy security, reliability, and resilience goals, Evolving customer engagement, Bifurcated energy demands, Increased interactions with other sectors, Local and global environmental concerns over air emissions, Energy access imperatives, Increasingly diverse participation in power markets, Revenue and investment challenges. Power Sector Finance: Regulations on commercial banking risk, Risk-premium environment for investments, Interest rates on government bonds, Capital availability from development authorities, Tax structures, Credit rating of electric utilities, Price and availability of inputs, Market structure and valuation constructs, Policy and regulatory environment.

ZS Fratzscher, *The Future of Utilities*, III. Utilities are experiencing an unprecedented change in their operating environment, which requires a broad reinvention of business models. Historically, a centralized and grid-connected power generation structure positioned utilities in the center of the power system, with a culture focused on regulators and mandates rather than innovation and customer service expectations. This utility business model is now profoundly questioned by the accelerated deployment of distributed energy resources and smart grid technologies, as well as profound changes in market economics and regulatory frameworks. This is a global trend, to which utilities and regulators around the world seek to find adequate solutions.

ZT Eichman et al., "Integration of Renewable Resources," 353. Three renewable deployment strategies are explored including all wind, all solar photovoltaic, and 50/50 mixture. Initially, wind is the preferred candidate from a cost and required installed capacity perspective; however, as the penetration increases excess wind generation encourages installation of solar. The 50/50 case becomes more cost competitive at high renewable penetrations (greater than 32.4%) and provides the highest system-wide capacity factor and CO_2 reduction potential. Results highlight the value of optimizing the renewable deployment strategy to minimize costs and emphasize the importance of considering capacity factor and curtailment when representing the true cost of installing renewables.

ZU Yang, Zhang, and Xiao, "Optimal Design," 433. The introduction of energy distribution networks and/or storages has significant and similar effects on optimal system configuration and can improve the system's economic efficiency because of the elimination of some of the strong coupling relation between demands and generators.

ZZ Friebe, Flotow, and Täube, "Exploring Technology Diffusion," 223–224. In fact, our qualitative results underline that in emerging markets Feed-in-Tariffs combined with guaranteed grid access are even more important than in industrialized countries. Both mechanisms considerably reduce comparatively high investment risk, which is typical for emerging countries. . . . Our results show that in emerging markets—in addition to technology-specific factors—generic influencing factors such as transparency and legal security for international private sector organizations must be considered. We add to the (renewable) energy policy literature, which focuses on policy formulation, by emphasizing these implementation factors for emerging markets.

ZAA Greene, German, and Delucchi, "Fuel Economy," 203. This suggests that increasing fuel prices may not be the most effective policy for increasing the application of technologies to increase passenger and light truck fuel economy. This view is supported by the similar levels of technology applied to U.S. and European passenger cars in the 1990s, despite fuel prices roughly three times higher in Europe. It is also circumstantially supported by the adoption by governments around the world of regulatory standard for light-duty vehicle fuel economy and carbon dioxide emissions.

ZAD Lízal and Tashpulatov, "Do Producers Apply a Capacity Cutting Strategy," 114. Producers could, however, withhold part of production facilities (i.e., apply a capacity cutting strategy) and thereby push more expensive production facilities to satisfy demand for electricity. This behavior could lead to a higher price determined through a uniform price auction. Using the case of the England and Wales wholesale electricity market we empirically analyze whether producers indeed did apply a capacity-cutting strategy. For this purpose we examine the bidding behavior of producers during high- and low-demand trading periods within a trading day. We find statistical evidence for the presence of capacity cutting by several producers, which is consistent with the regulatory authority's reports.

APPENDIX III: EMPIRICAL EVIDENCE ON POLICY DIRECTLY EVALUATING PRICE IN THE CLIMATE CHANGE ANALYSIS

Limitations of Markets

Market failures (incumbency, uncertainty, collective action, principle agent, low WTP) (16, 34, 37, 38, 73, 98, 115, 123, 130, 137, D)

Market power (123, 137, ZAD)

Non-market Factor (35, 50, ZO, ZP)

Complex causes of adoption (34, 115, 183, ZZ, ZAC)

Institutional capacity is crucial to effective, least-cost implementation (17, 50, 105, 106, 119, 120, 161)

Technology transfer and learning play a key role (90, 110, 130, D)

Integration: Challenge and Response (5, 13, 18, 54, 56, 58, 114, 138, 139, 199, 201, ZT, ZU)

Inertia v. Urgency (6, 59, 126, 202, F, ZQ)

  Avoid lock in (7, 69, 89, 106, J)

  Early action lowers the transitional and total economic (41, 6, 69, 70, 83, 101, 106)

Evidence on Price and Other Policies (3)

The ineffectiveness of price/ Tax as policy

  Price Insufficiency (4, 11, 15, 19, 20, 25, 29, 63, 70, 81, 82, 102, 144, 160, 188, 191, 193, A, L, S)

Tax: Difficulty of setting and sustaining "optimal" levels (81, 82, 160, B)

Tradable permits do not increase innovation (22, 147, 191, C)

Effective Policy Responses (ZR, ZS)

Public goods (101, 195, ZC)

Institution Building (90, 94, 110, 195, ZN, ZE)

Research and Development (22, 57, 82, 97, 101, 102, 103, 106, 130, 141, 148, 188, ZD, ZF)

Capital subsidies Adders, premium prices (25, 160, ZG, ZY)

Obligations/Consenting (101, 102, 106, 141, 188, M, (ZH, ZS, ZAA)

Standards (44, 90, 100, 171, 172, ZI, ZX)

Feed in Tariffs (106, 1156, 60, 182, 188, ZJ)

Merit order (27, 67, 85, ZK)

Flexible, overlapping policies are needed that recognize complexity (17, 81, 125, 126, 130, 152, 169, 179, E, ZV, ZAF)

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Citations

A Walz, Schleich, and Ragwitz, *Regulation, Innovation and Wind Power Technologies*, 16. Power prices, however, are not found to drive patent activity. Hence power prices alone would likely not be sufficient to spur innovation activities in wind and arguably also other, currently less cost-efficient renewable technologies.

B The stability and long-term vision of policy target setting are important policy style variables, which contribute to the legitimacy of technology and provide guidance of search.

C Calel and Dechezloprete, "Directed Technological Change," 1. More refined estimates that combine matching methods with different-in-difference provide evidence that the EU ETS has not impacted the direction of technological change. This finding appears to be robust to a number of stability and sensitivity checks. While we cannot completely rule out the possibility that the EU ETS has impacted only large companies for which suitable unregulated comparators cannot be found, our findings suggest that the EU ETS so far has had at best a very limited impact on low-carbon technological change.

D Massetti and Nicita, *Optimal Climate Policy*, 1. The presence of market failures in the R&D sector, as emphasized by Griliches, is confirmed by the evidence, virtually found in all studies, that the social rate of return on R&D expenditure is higher than the corresponding private rate; estimates of the marginal social rate of return on R&D range between 30 and 50 percent and of private return between 7 and 15 percent. . . . When it comes to technologies for carbon emissions reduction, the difference between private and social rate of return to R&D investment arises from a double externality; the presence of both environmental and knowledge externalities. First, without a price on carbon that equates the global and the private cost of emitting GHGs, all low emissions technologies are relatively disadvantaged and the level of investment is therefore sub-optimal. Second, the private return to investment in R&D is lower than the social return of investment due to the incomplete appropriability of knowledge creation, thus pushing further away investment for the socially optimal level.

E Massetti and Nicita, *Optimal Climate Policy*, 17. We find that a [carbon] stabilization policy together with an R&D policy targeted at the only energy sector is significantly less costly than the stabilization policy alone. We find that energy R&D does not crowd out non-energy R&D, and thanks to intersectoral spillovers, the policy-induced increase in energy efficiency R&D spills over to the non-energy sector, contributing to knowledge accumulation and the reduction of knowledge externalities.

F Gross, *On Picking Winners*, 18. The phenomenon of "learning by doing", whereby costs for technologies reduce as experience is gained from deployment of the technology creates lock-in. It also creates better, cheaper technologies. The incumbent fossil and nuclear forms of generation have had many decades of technical refinement through experience which have driven their costs down to low levels relative to new, renewable technologies. In part, this was financed by considerable public subsidy. . . . The very same effects that created lock-in to high carbon systems offer the potential to decrease the costs and improve the commercial/consumer attractiveness of new forms of low carbon energy.

J Kalkuhl, Edenhofer, and Lessmann, "Learning or Lock-In," 10. The energy sector is highly vulnerable to lock-in because electricity is an almost perfect substitute for consumers. In contrast, many innovations in the manufacturing or entertainment electronics sector provide a new product different from existing ones (e.g. flat screens vs. CRT monitor). The low substitutability implies a high niched demand and, thus, provokes ongoing learning-by-doing although considerable spillovers exist and market prices are distorted.

L Gross, *On Picking Winners*, 10. Either policymakers around the world are blind to the logic of economic theory, or there are factors that overwhelm or undermine the theoretical Pigouvian considerations. The rest of this paper discusses the considerations t

P Reuter et al., "Renewable Energy Investment," 253. If there is uncertainty about the future development of feed-in-tariffs, much higher levels will be needed to make renewable investment attractive for energy companies.

S Gross, *On Picking Winners*. In short, whilst carbon pricing can create conditions that make investment in wind more attractive, there are uncertainties associated with wholesale power prices, carbon permit prices, and future political decisions on carbon tax levels. These make wind investment more risky, which drives up the cost of capital-investors require higher returns), and discourage investment.

ZC Horbach, "Environmental Innovations," 172. An environmentally oriented research policy has not only to regard traditional instruments like the improvement of the technological capabilities of a firm but also the coordination with soft environmental policy instruments like the introduction of environmental management systems.

ZD Johnstone and Hascic, *Directing Technological Change*, 25. Since innovating in storage technologies is an important complement to innovation in all intermittent renewable generating technologies such a strategy reduces the risk of (not) picking winners. Moreover, the technologies are at a relatively early stage of development, with greater need for support.

ZE Wilson et al., "Marginalization of End Use Technologies," 781. The institutions emphasized in our analytic framework are twofold: the propensity of entrepreneurs to invest in risky innovation activities with uncertain pay-offs; and shared expectation around an innovation's future trajectory. Other important and related institutions include law, markets, and public policy. Public resources are invested directly into specific innovation stages, or are used to leverage private sector resources through regulatory or market incentives structured by public policy. . . . New technologies successfully diffuse as a function of their relative advantage over incumbent technologies. For energy technologies, this can be measured by the difference in cost and performance of energy service provision in terms of quality, versatility, environmental impact and so on. Many of these attributes of relative advantage can be shaped by public policy as well as the other elements of the innovation system.

ZF Walz, Schleich, and Ragwitz, *Regulation, Innovation and Wind Power Technologies*, 5. The specific advantage of feed-in tariffs is seen in lower transaction costs and reduced risk perception for investors and innovators, which are extremely important especially for new entrants and for financial institutions.

ZG Rubbeike and Weiss, *Environmental Regulations*. Including non-price-based variables increases the fit of the model. . . . The coefficients for grants is positive and highly significant.

ZH Walz, Schleich, and Ragwitz, *Regulation, Innovation and Wind Power Technologies*, 16. Our econometric analyses also imply that the existence of targets for renewables/wind and a stable policy-support environment are associated with higher patent activity.

ZI de Cian and Massimo, "Mitigation Portfolio," 133, 135. Against this evidence, regulation such as Emissions Performance Standards (EPS) that set a maximum threshold for the emission intensity of power generation in terms of grams of CO_2 per kilowatt hour could be justified as a way to reduce uncertainty exposure. . . . We have also pointed out that the optimal penetration of renewables is slow, even when facing a given deterministic carbon price.

ZJ Gross, Blyth and Heptonstall, "Risks, Revenues and Investment," 802. The international evidence suggests that in most cases countries with fixed price schemes have been more successful at deploying renewables than those with trading schemes. Whilst the reasons for this are complex and varied it appears likely that investment risk plays an important role.

ZK Gross, Blyth and Heptonstall, "Risks, Revenues and Investment," 798. The result is that significant long-run fuel price uncertainty . . . cannot usually be hedged through contractual arrangements. Long-run fuel price changes, like time of day rates, are mediated by the current market arrangements but remain fundamental to electricity prices.

ZN Inoue, Arimura, and Nakano, "A New Insight into Environmental Innovation," 162. Our finding shows that the organizational and managerial factors of firms are important in examining environmental R&D.

ZO Cordes and Schwesinger, "Technological Diffusion," passim. Proposition 1. Preference acquisition processes based upon social learning can override a technology's relative cost and/

or hedonistic disadvantages and therefore lead to its diffusion in a population of interacting adopters. . . . Proposition 2. If a dedicated cultural role model takes effect in consumers' preference learning during certain critical time spans or "windows of opportunity," it can persistently promote the diffusion of a green technology. . . . Proposition 3. State regulation that temporarily creates a niche for a green technology by preventing competitive impacts of other technologies can help decrease its cost or hedonistic disadvantages by gaining adopters in the niche market. Subsequently, a technology can be able to diffuse further even after the removal of this kind of governmental protection. . . . Proposition 4. Environmental policy instruments that comprise the promotion of "green preferences" via social learning in combination with measures to lower relative cost disadvantages can be expected to be more efficient and effective as to the fostering of a green technology's diffusion in a population of interacting adopters.

ZP Spence et al., "Public Perceptions," 550. We show that, although cost is likely to be a significant reason for many people to take up DSM measures, those concerned about energy costs are actually less likely to accept DSM. Notably, individuals concerned about climate change are more likely to be accepting. A significant proportion of people, particularly those concerned about affordability, indicated unwillingness or concerns about sharing energy data, a necessity for many forms of DSM. We conclude substantial public engagement and further policy development are required for widespread DSM implementation.

ZQ Zinaman et al., "Power Systems of the Future," 113, 125. Rapid cost reductions—for example, of photovoltaic modules—have changed the economic landscape for what is feasible. Yet established asset bases, and their supporting business models and regulatory frameworks, still retain significant inertia in most power systems. These longstanding financial and institutional ''legacy" arrangements promote incremental change. . . . Whether the trends outlined in Section II are ''headwinds" or ''tailwinds" will depend on the orientation set by decision makers for their power systems. Policymakers and regulators can choose to let these external forces determine how power systems unfold, or they can promote policies and build regulatory and finance frameworks that drive the transformation toward a desired vision. As a final organizing principle, early and frequent stakeholder engagement will encourage the emergence of modern power systems that accommodate a broad set of interests and best serve citizens and energy customers.

ZR Zinaman et al., "Power Systems of the Future," passim. Trends: Ten Trends: Renewable energy cost reductions, Innovations in data, intelligence, and system optimization, Energy security, reliability, and resilience goals, Evolving customer engagement, Bifurcated energy demands, Increased interactions with other sectors, Local and global environmental concerns over air emissions, Energy access imperatives, Increasingly diverse participation in power markets, Revenue and investment challenges. Power Sector Finance: Regulations on commercial banking risk, Risk-premium environment for investments, Interest rates on government bonds, Capital availability from development authorities, Tax structures, Credit rating of electric utilities, Price and availability of inputs, Market structure and valuation constructs, Policy and regulatory environment.

ZS Fratzscher, *The Future of Utilities*, III. Utilities are experiencing an unprecedented change in their operating environment, which requires a broad reinvention of business models. Historically, a centralized and grid-connected power generation structure positioned utilities in the center of the power system, with a culture focused on regulators and mandates rather than innovation and customer service expectations. This utility business model is now profoundly questioned by the accelerated deployment of distributed energy resources and smart grid technologies, as well as profound changes in market economics and regulatory frameworks. This is a global trend, to which utilities and regulators around the world seek to find adequate solutions.

ZV Weigt, Ellerman, and Delarue, "CO_2 Abatement," 152. Two features stand out. First, as implemented in Germany, RES policy is much more effective in reducing CO_2 emissions within the German electricity sector than the EU ETS. The emission impact of the EUA price is in the range of 1 to 3% compared to an 11 to 20% impact of RE generation. Second, the abatement attributable to each instrument is greater when that instrument is deployed in conjunction with the other. Alternatively, when employed together, the abatement is greater than the sum of the individual abatement effects when each instrument is deployed individually.

ZX Siderius, "Setting MEPS," 1. The results imply that the classical approach of setting minimum efficiency performance standards (MEPS) by means of life cycle cost calculations can not be applied to electronic products. Therefore, an alternative approach based on the improvement of efficiency over time and the variation inefficiency of products on the market, is presented. The concept of a policy action window can provide guidance for the decision on whether setting MEPS for a certain product is appropriate. If the (formal) procedure for setting MEPS takes longer than the policy action window, this means that the efficiency improvement will also be achieved without setting MEPS. We found short, i.e., less than three years, policy action windows for graphic cards, network attached storage products, network switches, and televisions.

ZY de la Rue du Can et al., "Design of Incentive Programs," 56. Incentives complement mandatory standards and labeling policies by accelerating market penetration of products that are more energy efficient than required by existing standards and by preparing the market for more stringent future mandatory requirements. Incentives can be directed at different points in the appliance supply chain; one point may be more effective than another depending on the technology's maturity and market penetration.

ZZ Friebe, Flotow, and Täube, "Exploring Technology Diffusion," 223–224. In fact, our qualitative results underline that in emerging markets Feed-in-Tariffs combined with guaranteed grid access are even more important than in industrialized countries. Both mechanisms considerably reduce comparatively high investment risk, which is typical for emerging countries. . . . Our results show that in emerging markets—in addition to technology-specific factors—generic influencing factors such as transparency and legal security for international private sector organizations must be considered. We add to the (renewable) energy policy literature, which focuses on policy formulation, by emphasizing these implementation factors for emerging markets.

ZAA Greene, German, and Delucchi, "Fuel Economy," 203. This suggests that increasing fuel prices may not be the most effective policy for increasing the application of technologies to increase passenger and light truck fuel economy. This view is supported by the similar levels of technology applied to U.S. and European passenger cars in the 1990s, despite fuel prices roughly three times higher in Europe. It is also circumstantially supported by the adoption by governments around the world of regulatory standard for light-duty vehicle fuel economy and carbon dioxide emissions.

ZAB Johnson, "The Cost of Carbon Dioxide Abatement," 33. Using my preferred elasticity estimate, I calculate the marginal cost of abatement from RPSs is at least \$11 per ton of CO_2 compared to a marginal cost of abatement of \$3 per ton in the Regional Greenhouse Gas Initiative.

ZAC Liu, "Barriers to the Adoption of Low Carbon Production," 12. Larger firms tend to have a more structured organization and lower perceptions of the employment term barrier. However, larger structured organizations have been affected by a long history of a planning-oriented economy and hence tend to have flexible hierarchical systems. In contrast, small firms have hierarchical systems with less effect on low carbon production than those of large enterprises. Another interesting trend is the direct size effect on cultural barriers, which is evident in a culture of risk aversion, as well as the lack of low carbon technology and the existence of silos between planning and production

ZAD Lízal and Tashpulatov, "Do Producers Apply a Capacity Cutting Strategy," 114. Producers could, however, withhold part of production facilities (i.e., apply a capacity cutting strategy) and thereby push more expensive production facilities to satisfy demand for electricity. This behavior could lead to a higher price determined through a uniform price auction. Using the case of the England and Wales wholesale electricity market we empirically analyze whether producers indeed did apply a capacity-cutting strategy. For this purpose we examine the bidding behavior of producers during high- and low-demand trading periods within a trading day. We find statistical evidence for the presence of capacity cutting by several producers, which is consistent with the regulatory authority's reports.

ZAF Luderer, “Economic Mitigation Challenges,” 6. Our work maps out the trade-offs between the stringency of climate targets and economic mitigation challenges at a very high level of detail. It shows how a continuation of ineffective climate policies reduces the option space for future climate policy, increasing mitigation challenges and the reliance on technologies for removing CO_2 from the atmosphere.

NOTES

CHAPTER 1

1. David W. Pearce, *The MIT Dictionary of Modern Economics* (Cambridge, MA: MIT Press, 1984), 342.

2. Thomas Piketty, *Capital in the Twenty-First Century*, trans. Arthur Goldhammer (Cambridge, MA: Belknap, 2014), 574.

3. The term was used explicitly in late 1998, although the ideas underlying the concept were criticized somewhat earlier. Stiglitz used it in his Nobel lecture in 2001. See "Market fundamentalism" at https://en.wikipedia.org/wiki/Market_fundamentalism.

CHAPTER 2

1. The international governance literature is vast. Our interpretation builds on analysis of the transnational governance of the Internet (Mark Cooper, "Why Growing Up is Hard to Do: Institutional Challenges for Internet Governance in the 'Quarter Life Crisis' of the Digital Revolution," *Journal on Telecommunications and High Technology Law* 11 [2013]). Three examples from the literature on international energy policy lead us to believe our analysis it applicable. Ann Florini and Benjamin K. Sovacool ("Who Governs Energy? The Challenges Facing Global Energy Governance," *Energy Policy* 37 [2009]) describe the weaknesses of various international institutions and the severe challenges that climate change poses, including urgency, geopolitical tensions, and economic vulnerabilities and call for collaboration between energy policy researchers and global governance scholars. The description of the Paris Agreement indicates a vigorous effort to confront these challenges that is consistent with the research literature. Andreas Goldthau ("A Public Policy Perspective on Global Energy Security," *International Studies Perspectives* 13 [2012], 65–84), identifies four classic sources of market failure that need to be addressed, lack of competition, externalities, public goods, and lack of information. The Paris Agreement is long on all of these. John Ravenhill ("Resource Insecurity and International Institutions in the Asia-Pacific Region," *The Pacific Review*, 26 [2013]: 1–15, doi:10.1080/09512748.2013.755364) identifies five levels of institutionalization: dialogue/information sharing, coordination (non-binding principles), negotiation of monitored targets, legally binding treaty, and governance though joint institutions. These activities are not mutually exclusive; they are all ongoing. The Agreement did not bind parties to

specific goals and the joint institutions do not have enforcement authority. In this sense it is soft, but, given the complexity of the economic terrain and the authority of nations, it went a long way.

2. The adjustment is necessary because of differences in the structure of costs between the resources. The low-carbon resources—wind, solar, and nuclear—are capital intensive, with capital costs and fixed O&M costs equal to 85 to 95 percent of total costs. Coal's capital and O&M costs are about two-thirds of total costs.

3. The recognition of the technological revolution came first in the academic literature, then in the popular press. See, for example, Ryan Avent, "Creating the Clean Economy," *The Economist*, June 11, 2011; David Leonhardt, "There's Still Hope for the Planet," *New York Times*, July 21, 2012.

4. Marshall Goldberg, *Federal Energy Subsidies: Not All Technologies Are Created Equal* (Washington, DC: Renewable Energy Policy Project, 2000); Nancy Pfund and Ben Healey, *What Would Jefferson Do? The Historical Role of Federal Subsidies in Shaping America's Energy Future* (San Francisco, CA: DBL Investors, 2011); Luis M. A. Bettencourt, Jessika E. Trancik, and Jasleen Kaur, "Determinants of the Pace of Global Innovation in Energy Technologies," *PLOS ONE* 8 (2013): 10, doi:10.1371/journal.pone.0067894.

5. Brian Eckhouse, "Batteries Gaining Favor over Gas Peaker Plants in California," *Bloomberg*, December 22, 2015.

6. RAP, general agreement on a "dividend" of 10–20 percent in reduced load, in addition to the benefits of reduced peak and system reliability.

7. UNFCCC, *Paris Agreement* (United Nations Framework Convention on Climate Change, 2015).

8. Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries*, December 13, 2015. Hereafter, we refer to this as Jacobson et al. in the text.

9. Greenpeace International, Global Wind Energy Council, and Solar Power Europe, *Energy [R]evolution: A Sustainable World Energy Outlook 2015* (Amsterdam, The Netherlands: Greenpeace International, 2015).

10. Deep Decarbonization Pathways Project, *Pathways to Deep Decarbonization 2015 Report* (Paris: SDSN – IDDRI, 2015).

11. Lazard, *Lazard's Levelized Cost of Energy Analysis* 9.0, November 2015, https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-90/. Although the graphs and calculations in this book are based on Lazard 9.0, Lazard 10.0, December 20, 2016, reinforces the conclusions based on 9.0, with the underlying trends for wind, solar, and storage continuing to unfold.

12. Electric Power Research Institute, *Australian Power Generation Technology Study* (Palo Alto, CA: EPRI, 2015), hereafter referred to in the text as the Australian LCOE Report.

13. Needless to say, examination of 100% renewable approaches to climate change have been appearing in the research literature for some time. See, for example, Claudia Ghisetti and Francesco Quatraro, "Beyond Inducement in Climate Change: Does Environmental Performance Spur Environmental Technologies? A Regional Analysis of Cross-Sectoral Differences," *Ecological Economics* 96 (2010); Goran Krajac, Neven Duic, and Maria da Graca Carvalho, "How to Achieve a 100% RES Electricity Supply for Portugal?," *Applied Energy* 88 (2011); D. Connolly et al., "The First Step towards a 100% Renewable Energy-System for Ireland," *Applied Energy* 88 (2011); Mark Z. Jacobson and Mark A. Delucchi, "Providing All Global Energy with Wind, Water, and Solar Power. Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials," *Energy Policy* 39 (2011); Mark A. Delucchi and Mark Z. Jacobson, "Providing All Global Energy

with Wind, Water, and Solar Power. Part II: Reliability, System and Transmission Costs, and Policies," *Energy Policy* 39 (2011). Ben Elliston, Iain MacGill, and Mark Disendorf, "Least Cost 100% Renewable Electricity Scenarios in the Australian National Electricity Market," *Energy Policy* 59 (2013), identifies studies prior to 2013; Jacquelin Cochran, Trieu Mai, and Morgan Bazilian, "Meta-Analysis of High Penetration Renewable Energy Scenarios," *Renewable and Sustainable Energy Reviews* 29 (2014), compare a dozen studies. Jacobson et al., *Roadmaps for 139 Countries*, provides more recent examples. There is a second professional trade literature, particularly from financial analysts that has demonstrated the economics of deep decarbonization, both in comprehensive reviews (for example, Jason Chanell et al., *Energy Darwinism II: Why a Low Carbon Future Doesn't Have to Cost the Earth* (New York: Citigroup, 2015) and, in particular, assessments of the economics of renewables in Dan Eggers, *Energy Efficiency: The Reality of Slower Power Demand Growth* (Credit Suisse, 2013); Dan Eggers, Kevin Cole, and Matthew Davis, *The Transformation Impact of Renewables* (Credit Suisse, 2014); and David Frankel, Kenneth Ostrowski, and Dickon Pinner, "The Disruptive Potential of Solar Power: As Costs Fall, the Importance of Solar Power to Senior Executives Is Rising," *McKinsey Quarterly*, 2014).

14. Throughout this analysis we use long term and long run interchangeably: "In microeconomics, the 'long run' is the conceptual time period in which there are no fixed factors of production, so that there are no constraints preventing changing the output level by changing the capital stock or by entering or leaving an industry. The long run contrasts with the short run, in which some factors are variable and others are fixed, constraining entry or exit from an industry," https://en.wikipedia.org/wiki/Long_run_and_short_run.

15. Jacobson et al., *Roadmaps for 139 Countries*, Table 2.

16. Deep Decarbonization, *Pathways*, Table 4.

17. Ibid., Executive Summary, Figure 7.

18. Ibid., Executive Summary, Figure 6.

19. Jacobson et al., *Roadmaps for 139 Countries*, 35. Two-fifths of the environmental and public health benefits are the result of carbon reduction.

20. Ibid., 1.

21. Ibid., 20.

22. Ibid., 13.

23. Mark Cooper, *Energy Efficiency Performance Standards: Driving Consumer and Energy Savings in California* (presentation at the California Energy Commission's Energy Academy, February 20, 2014), presents a review of the efficiency literature. Recent analyses that support the large potential include Priya Sreedharan, "Recent Estimates of Energy Efficiency Potential in the USA," *Energy Efficiency* 6 (2013); Virginie E. Letschert et al., *Energy Efficiency Appliance Standards: Where Do We Stand and How Far Can We Go and How Do We Get There? An Analysis Across Several Economies* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2013); Gouri Shankar Mishra et al., "Mitigating Climate Change: Decomposing the Relative Roles of Energy Conservation, Technological Change, and Structural Shift," *Energy Economics* 44 (2014).

24. Bureau of Resources and Energy Economics, *Australian Energy Technology Assessment* (Australian Government, 2012); Mark Cooper, *Nuclear Power Is an Expensive, Inferior Resource That Has No Place in a Least-Cost, Low-Carbon Portfolio* (submission to the Electricity Generation from Nuclear Fuels, Nuclear Fuel Cycle Royal Commission, August 3, 2015), demonstrates the general relevance of the global analysis to Australia.

25. UNFCCC, *Paris Agreement*, 2.

26. Ibid., 3.

27. Ibid., 4.

28. Ibid., 2.
29. Ibid., 10.
30. Ibid., 21.
31. Ibid., 21.
32. Ibid., 2.
33. Ibid., 9–10.
34. Ibid., 23.
35. Least cost principles have long been the central pillar of regulatory economics; see, e.g., Mark Cooper, *Least Cost Planning for 21st Century Electricity Supply: Meeting the Challenges of Complexity and Ambiguity in Decision Making* (paper presented at the Mid-America Regulatory Utility Conference, June 5, 2011); Mark Cooper, *Prudent Resource Acquisition in a Complex Decision Making Environment: Multidimensional Analysis Highlights the Superiority of Efficiency* (paper presented at Current Approaches to Integrated Resource Planning, 2011 ACEEE National Conference on Energy Efficiency as a Resource, Denver, September 26, 2011a). In climate change analysis they were given intense, practical voice in studies by energy consultants; see, e.g., John Rowe, *Energy Policy: Above All, Do No Harm* (American Enterprise Institute, March 8, 2010); Rowe, *Fixing the Carbon Problem Without Breaking the Economy* (resources for the Future Policy Leadership Forum Lunch, May 12, 2010).
36. Mitigation is the master strategy, but as significant impacts appear to be unavoidable, adaptation is recognized as a strong complementary strategy both to alleviate harms and to capture synergies that can lower total costs. Klein et al., "Inter-Relationships Between Adaptation and Mitigation," in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Martin Parryet et al. (Cambridge, UK: Cambridge University Press, 2007); Julia Illman et al., *Scoping Study on Financing Adaptation-Mitigation Synergy Activities* (Copenhagen: Nordic Council of Ministers, 2013); Mia Landauer, Sirkku Juhola, and Maria Söderholm, "Inter-Relationships Between Adaptation and Mitigation: A Systematic Literature Review," *Climatic Change* 131 (2015).
37. Michael Grubb, Thierry Chapuis, and Minh Ha Duong, "The Economics of Changing Course: Implications of Adaptability and Inertia for Optimal Climate Policy," *Energy Policy* 23 (1995); David Popp, Richard G. Newell, and Adam B. Jaffee, "Energy, the Environment, and Technological Change," in *Economics of Innovation*, ed. Bronwyn H. Hall and Nathan Rosenberg (Amsterdam: North-Holland, 2010); Antoine Dechezleperte et al., *Climate Change & Directed Innovation: Evidence from the Auto Industry* (London: London School of Economics and Political Science, 2011); Nick Johnstone and Ivan Hascic, *Directing Technological Change while Reducing the Risk of (Not) Picking Winners: The Case of Renewable Energy* (OECD Environment Directorate, 2010); Gunnar Luderer, "Economic Mitigation Challenges: How Further Delay Closes the Door for Achieving Climate Targets," *Environmental Research Letters* 8 (2013).
38. Reyer Gerlagh, "Measuring the Value of Induced Technological Change," *Energy Policy* 35 (2007); Reyer Gerlagh, Snorre Kverndokk, and Knut Einar Rosendhal, "Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities," *Environmental Resource Economics* 43 (2009); Matthais Kalkuhl, Ottmar Edenhofer, and Kai Lessmann, "Learning or Lock-in: Optimal Technology Policies to Support Mitigation," *Resource and Energy Economics* 34 (2012); Daron Acemoglu and James A. Robinson, *Why Nations Fail: The Origins of Power, Prosperity, and Poverty* (New York: Crown Publishers, 2012); Robert Gross et al., *On Picking Winners: The Need for Targeted Support for Renewable Energy* (London: Imperial College London, 2012); Ted Nordhaus, Alex Trembath, and Michael Shellenberger, "Carbon Taxes and Energy Subsidies: A

Comparison of the Incentives and Costs of Zero-Carbon Deployment," *Breakthrough Institute,* September 12, 2012. This observation has crossed over to the popular press: Leonhardt, "There's Still Hope"; Avent, "Creating the Clean Economy."

39. Peter H. Kobos, Jon D. Erickson, and Thomas E. Drennen, "Technological Learning and Renewable Energy Costs: Implications for U.S. Renewable Energy Policy," *Energy Policy* 34 (2006); Jon Horbach, "Determinants of Environmental Innovations—New Evidence from German Panel Data Source," *Research Policy* 37 (2008); Helene Ahlborg, "Provision of Electricity to African Households: The Importance of Democracy and Institutional Quality," *Energy Policy* 87 (2015); Ron Boschma and Gianluca Capone, "Institutions and Diversification: Related Versus Unrelated Diversification in a Varieties of Capitalism Framework," *Research Policy* 44 (2015); Harald Heubaum and Frank Biermann, "Integrating Global Energy and Climate Governance: The Changing Role of the International Energy Agency," *Energy Policy* 87 (2015).

40. Valentina Bosetti and Enrica De Cian, "A Good Opening: The Key to Make the Most of Unilateral Climate Action," *Environmental and Resource Economics* 56 (2013); Ek and Soderholm, "Technology Learning in the Present of Public R&D: The Case of European Wind Power," *Ecological Economics* 69 (2010); Sondes Kahouli Brahmi, "Technological Learning in Energy-Environment-Economy Modeling: A Survey," *Energy Policy* 36 (2008); Kalkuhl, Edenhofer, and Lessmann, "Learning or Lock-In"; Asa Lindman and Patrik Soderholm, "Wind Power Learning Rates: A Conceptual Review and Meta-Analysis," *Energy Economics* 34 (2012); Edward S. Rubin, "A Review of Learning Rates for Electricity Supply Technologies," *Energy Policy* 86 (2015); Theres Lindahl, Örjan Bodin, and Maria Tengö, "Governing Complex Commons—The Role of Communication for Experimental Learning and Coordinated Management," *Ecological Economics* 111 (2015).

41. Yueming Qui and Laura D. Anadon, "The Price of Wind in China During Its Expansion: Technology Adoption, Learning-by-Doing, Economies of Scale, and Manufacturing Localization," *Energy Economics* 34 (2012); David Toke, Sylvia Breukers, and Maarten Wolsnik, "Wind Power Deployment Outcomes: How Can We Account for the Differences?," *Renewable and Sustainable Energy Review* 12 (2008); Lubomír Lízal and Sherzod N. Tashpulatov, *Can Producers Apply a Capacity Cutting Strategy to Increase Prices? The Case of the England and Wales Electricity Market* (Prague: The Center for Economic Research and Graduate Education—Economics Institute, 2012); Chulwoo Baek, Euy-Young Jung, and Jeong-Dong Lee, "Effects of Regulation and Economic Environment on the Electricity Industry's Competitiveness: A Study Based on OECD Countries," *Energy Policy* 72 (2014); Camille Gonseth, "Energy-Tax Changes and Competitiveness: The Role of Adaptive Capacity," *Energy Economics* 48 (2015).

42. André Grimaud and Gilles Lafforgue, "Climate Change Mitigation Policies: Are R&D Subsidies Preferable to a Carbon Tax?," *Revue d'économie politique* 119 (2008); Stephane de la Rue du Can et al., "Design of Incentive Programs for Accelerating Penetration of Energy-Efficient Appliances," *Energy Policy* 72 (2014); Cheng Zheng and Daniel M. Kammen, "An Innovation-Focused Roadmap for a Sustainable Global Photovoltaic Industry," *Energy Policy* 67 (2014); Gireesh Shrimali, Melissa Lynes, and Joe Indvik, "Wind Energy Deployment in the U.S.: An Empirical Analysis of the Role of Federal and State Policies," *Renewable and Sustainable Energy Reviews* 43 (2015); Leslie Shiell and Nikita Lyssenko, "Climate Policy and Induced R&D: How Great Is the Effect?" *Energy Economics* 46 (2014); Bikash Kumar Sahu, "A Study on Global Solar PV Energy Developments and Policies with Special Focus on the Top Ten Solar PV Power Producing Countries," *Renewable and Sustainable Energy Reviews* 43 (2015); Hong-Bo Duan, Lei Zhu, and Ying Fan, "Modelling the Evolutionary Paths of Multiple Carbon-Free Energy Technologies with Policy Incentives," *Environmental Modeling and Assessment* 20 (2015).

43. The debate over sustainable growth is huge. The Paris Agreement seems to embrace the proposition that development and decarbonization goals can be reconciled, which finds support among some economists, e.g., Jeffrey D. Sachs, *The Age of Sustainable Development* (New York, NY: Columbia University Press, 2015), and some environmentalists, e.g., Johan Rockstrom and Mattias Klum, *Big World, Small Planet: Abundance Within Planetary Boundaries* (New Haven, CT: Yale University Press, 2015).

44. Cooper, "Why Growing Up Is Hard to Do," presents a discussion of the structure of commons governance applied to the Internet as a focal core resource system and the challenge of multinational governance. Mark Cooper, *Governing the Spectrum Commons*, presentation at the Telecommunications Policy Research Conference, October, 2006, demonstrates the core concept of rules with respect to the management of radio spectrum.

45. Elinor Ostrom, *Understanding Institutional Diversity* (Princeton, NJ: Princeton University Press, 2005), Chapters 7 and 9.

46. Elinor Ostrom, "Beyond Markets and States: Polycentric Governance of Complex Economic Systems," in *La Prix Nobel*, ed. Karl Grandin (Stockholm, Sweden: Nobel Foundation, 2010), 435–436.

47. Ostrom, *Understanding Institutional Diversity*, 278 (citation and footnotes omitted). Obtaining reliable information about the effects of different uses of resource systems and resource conditions is an activity that is essential to long-term sustainability. If all local communities were to have to develop all of their own scientific information about the physical settings in which they were located, few would have the resources to accomplish this.

48. Ostrom, *Understanding Institutional Diversity*, 278 (citation and footnotes omitted). "While smaller-scale, community-governed resource institutions may be more effective than centralized government in achieving many aspects of sustainable development, the absence of supportive, large-scale institutional arrangements may be just as much a threat to long-term sustenance as the presence of preemptive large-scale governmental agencies." Elinor Ostrom, "A General Framework for Analyzing Sustainability of Social-Ecological Systems," *Science* 325 (2009): 422. "Furthermore, the long-term stability of rules devised at a focal . . . level depends on monitoring and enforcement as well as their not being overruled by larger government policies. . . . Larger scale governance systems may either facilitate or destroy governance systems at a focal . . . level."

49. Douglass C. North, *Understanding the Process of Economic Change* (Princeton, NJ: Princeton University Press, 2005), 89.

50. "Degrowth thinkers and activists advocate for the downscaling of production and consumption—the contraction of economies—arguing that overconsumption lies at the root of long term environmental issues and social inequalities. Key to the concept of degrowth is that reducing consumption does not require individual martyring or a decrease in well-being. Rather, 'degrowthists' aim to maximize happiness and well-being through non-consumptive means—sharing work, consuming less, while devoting more time to art, music, family, culture and community." https://en.wikipedia.org/wiki/Degrowth.

51. Philip Lawn, "Is Steady-State Capitalism Viable? A Review of the Issues and an Answer in the Affirmative," in *Ecological Economics Reviews*, ed. R. Costanza, K. Limburg, and I. Kubiszewski (New York: New York Academy of Sciences, 2011), 1–25; and Daly as explained by Lawn, Sachs, *Sustainable Development*; Rockstrom and Klum, *Big World, Small Planet*, and the Paris Agreement).

52. Martin Fritz and Max Koch, "Potentials for Prosperity Without Growth: Ecological Sustainability, Social Inclusion and the Quality of Life in 38 Countries," *Ecological Economics* 108 (2014), 191.

53. Mark Cooper, *Power Shift, The Nuclear War Against the Future: How Nuclear Advocates Are Thwarting the Deployment of a 21st Century Electricity Sector*, Institute for Energy and the Environment, Vermont Law School, May, 2015.

54. Lawn, "Steady-State Capitalism"; Christian Kerschner, "Economic De-Growth vs. Steady-State Economy," *Journal of Cleaner Production* 18 (2010): 544–551; Herman Daly, *Ecological Economics and Sustainable Development: Selected Essays of Herman Daly* (Cheltenham: Edward Elgar Publishing, 2007).

CHAPTER 3

1. Explicit attempts to explore the relationships between the various schools include Nuno Ornelas Martins, "Sen's Capability Approach and Post Keynesianism: Similarities, Distinctions, and the Cambridge Tradition," *Journal of Post Keynesian Economics* 31 (2009); Hilary Putnam and Vivian Walsh, *The End of Value Free Economics* (Abingdon, Oxford: Routledge, 2012); and David Dequech, "Neoclassical, Mainstream, Orthodox and Heterodox Economics," *Journal of Post Keynesian Economics*, 30 (2007). The shared critique of the neoclassical/*laissez faire* model and the high-level theoretical lineage has led to examinations of and cross fertilization between middle-level models including institutional, ecological, and evolutionary approaches. See Geoffrey M. Hodgson, "Evolutionary and Institutional Economics as the New Mainstream?" *Evolutionary and Institutional Economics Review* 4 (2007) and "Institutional Economics into the Twenty-First Century," *Studi e Note di Economia* 14 (2009); Nuno Ornelas Martins, "The Place of the Capability Approach within Sustainability Economics," *Ecological Economics* 95 (2013); John Gowdy, "Contemporary Welfare Economics and Ecological Economics Valuation and Policy," *Internet Encyclopaedia of Ecological Economics*, International Society for Ecological Economics, February, 2003; John Gowdy et al., "The End of Faith-Based Economics," *The Corporate Examiner* 37 (2010).

2. Hodgson, "Institutional Economics."

3. Acemoglu and Robinson, *Why Nations Fail*, 74. "Inclusive Institutions . . . are those that allow and encourage participation by the great mass of people in economic activities that make best use of their talents and skills and then enable individuals to make the choices they wish. To be inclusive, economic institutions must feature secure private property, an unbiased system of law, and a provision of public services that provides a level playing field in which people can exchange and contract; it also must permit the entry of new business and allow people to choose their careers."

4. Ibid., 43.

5. Ibid., 75.

6. Frederic M. Scherer and David Ross, *Industrial Market Structure and Economic Performance* (3rd ed.; Boston, MA: Houghton Mifflin, 1990), 5, lists six policies in their depiction of the Structure-Conduct-Performance paradigm. Taxes are listed first, regulation second (followed by two other policies that are clearly regulatory, international trade rules and price controls), antitrust and information provision. Kip Viscusi, John M. Vernon, and Joseph E. Harrington, Jr., *Economics of Regulation and Antitrust* (Cambridge, MA: MIT Press, 2000), 3, see "two types of mechanisms . . . to address these departures from the perfectly competitive model . . . a tax on various types of activities . . . try to control behavior directly . . . in the field of antitrust . . . a complex web of regulation."

7. Acemoglu and Robinson, *Why Nations Fail*, 81, 84, 86. Scherer and Ross, *Industrial Market Structure*, 6, emphasize that three are feedback loops in the Structure-Conduct-Performance paradigm that technological change can be endogenous.

8. Daron Acemoglu and James A. Robinson, "The Rise and Decline of General Laws of Capitalism," *Journal of Economic Perspectives*, 29 (2015): 4. Piketty, *Capital*, 10, offers a similar explanation. "[Marx,] [l]ike his predecessors, totally neglected the possibility of durable technological progress and steadily increasing productivity, which is a force that can to some extent serve as a counterweight to the process of accumulation and concentration of private capital. He no doubt lacked the statistical data needed to refine his predictions. He probably suffered as well from having decided on this conclusion in 1848."

9. Elizabeth Anderson, "How Not to Complain about Taxes (III): 'I Deserve My Pretax Income,'" *Left2Right*, January 26, 2005, 2–3.

10. Ibid.

11. Carlota Pérez, "After the Crisis: Creative Construction," *Open Democracy News Analysis*, March 5, 2013, 4.

12. Carlota Pérez, "The Financial Crisis and the Future of Innovation: A View of Technical Change with the Aid of History," *Working Papers in Technology Governance and Economic Dynamics* 28 (2010), 23.

13. Carlota Pérez, "Long-Run Economic Transformation: After the Crisis: Technology, Globalisation and the Environment," in *OME Annual Report 2009–2010* (Barcelona, Spain: Government of Catalonia, 2010), 4.

14. Carlota Pérez, *The Advance of Technology and Major Bubble Collapses: Historical Regularities and Lessons for Today*, Engelsberg Seminar on "The Future of Capitalism," Axson Foundation, Sweden, June, 2010, 6–7.

15. Ibid., 7.

16. Pérez, "The Financial Crisis," 23.

17. The dual nature of key elements of the political economy—the entanglement of means and ends, which creates a tendency for endogenous change and great complexity and openness of systems—is seen as an important cause of the failure of the neoclassical model, which requires that means and ends be separate in the analysis to ensure a closed system and a value-free economic interpretation. See Hodgson, "Institutional Economics," 2009 (on institutions); Martins, "Sen's Capability Approach"; and Ivo Šlaus and Garry Jacobs, "Human Capital and Sustainability," *Sustainability* 3 (2011), on human capital.

18. The first paragraph of the Wikipedia entry on jurisprudence ends with the observation that, "Contemporary philosophy of law, which deals with general jurisprudence, addresses problems in two rough groups," one of which involves how a particular social institution "relates to the larger political and social situation in which it exists." The final theorist identified in the jurisprudence entry is John Rawls, "considered one of the most important English-language political philosophers of the 20th century" (http://en.wikipedia.org/wiki/Jurisprudence). Anderson adopts Sen's concept of capabilities. Martins, "Sen's Capability Approach," demonstrates the complementarity and consistency of Sen and Keynes, in addition to arguing for the integration of the economic model and moral frame.

19. Putnam and Walsh, *End of Value Free Economics*.

20. Elizabeth Anderson, "How Should Egalitarians Cope with Market Risks?" *Theoretical Inquiries in Law* 9 (2007), 268.

21. Mark Cooper, "Progressive, Democratic Capitalism in the Digital Age," paper presented at the Fund for Constitutional Government Conference on Media, Democracy and the Constitution," September 27, 2000; "Restoring the Balance of Public Values and Private Incentives in American Capitalism," in *Too Much Deregulation or Not Enough?* (Washington, DC: Cato Institution, 2002); "Open Architecture as Communications Policy," Stanford Law School, Center for Internet and Society, 2004.

22. Elizabeth Anderson, "Ethical Assumptions of Economic Theory: Some Lessons from the History of Credit and Bankruptcy," *Ethical Theory and Moral Practice* 7 (2004), 358; "Beyond *Homo Economicus*: New Developments in Theories of Social Norms," *Philosophy and Public Affairs* 29 (2000), 172–173.

23. Anderson, "Ethical Assumptions," 347, 357, 358.

24. Anderson, "How Should Egalitarians Cope," 243.

25. Elizabeth Anderson, "Equality and Freedom in the Workplace: Recovering Republican Insights," *Social Philosophy and Policy* 31 (2015), 11, 13, 14, 15.

26. Elizabeth Anderson, "Thomas Paine's 'Agrarian Justice' and the Origins of Social Insurance," in *Ten Neglected Classics of Philosophy*, ed. Eric Schliesser, 55–83 (New York, NY: Oxford University Press, 2017), 11.

27. Anderson, "How Should Egalitarians Cope," 239.

28. Anderson, "Equality and Freedom," 10, 15.

29. Elizabeth Anderson, "What Is the Point of Equality?" *Ethics* 109 (1999), 322–323.

30. Anderson, "What Is the Point?," 321.

31. Scherer and Ross, *Industrial Market Structure*, 4.

32. Ibid., 4.

33. Ibid., 7.

34. Ibid., 18.

35. Ibid.

36. With the emphasis on the impersonal process of competitive markets and freedom to choose, competitive economic markets are also preferred because they provide a strong basis for democratic political systems.

37. Scherer and Ross, *Industrial Market Structure*.

38. Alfred E. Kahn, *The Economics of Regulation: Principles and Institutions* (Cambridge, MA: MIT Press, 1988).

39. Ibid.

40. Ibid., 11.

41. Ibid.

42. Ibid.

43. Ibid., 114.

44. Mark Cooper, "The Long History and Increasing Importance of Public Service Principles for 21st Century Public Digital Communications Networks," *Journal on Telecommunications and High Technology Law* 12 (2014).

45. Lester D. Taylor, *Telecommunications Demand in Theory and Practice* (Dordrecht, The Netherlands: Kluwer Academic Publishers, 1994), 262. Taylor identifies three characteristics of necessities: inability to replace the good, large relative size of the expenditure, and importance of the good in a broad sense. "The point of departure will be to remind ourselves of a point that is probably too often forgotten: that price elasticity consists of two components, an income effect and a substitution effect. The substitution effect is a measure of the extent to which goods and services can substitute for one another when there is a price change without making the consumer any worse off in terms of consumer welfare. The income effect, on the other hand is a measure of the extent to which the consumer's real income is changed when there is a change in price. Ordinarily, the importance of the income effect is represented by the importance of the good whose prices have changed in the consumer's budget. Goods whose expenditure account for a small proportion of the consumer's total expenditures will have a small (or even tiny) income effect, while a good whose expenditures account for a large portion of total expenditure will have a possibly large income effect. Goods that in ordinary discourse are seen as necessities (such as heating fuels and telephone service) will also have relatively larger income effects the lower the level of income."

46. Ibid., "In assessing income effects, however, a point that is usually overlooked is the effect on the consumer's welfare of not consuming a good because of a price increase. In the case of making or not making a phone call because it has become more expensive, the question that needs to be asked is what are the consequences (not necessarily in monetary terms) of not making the call. For residential consumers, this cost is usually cast in term of the utility (or satisfaction) that is given up by the call not being made. For many calls, however, this is not the correct measure of cost, for the call may be important to the *earning* of income. In this case, the actual income effect of not making a telephone call may be large, although the decrease in real income (as customarily measured), occasioned by the price increase may be extremely small."

47. Kahn, *The Economics of Regulation*, 11.

48. Francis, *Laudato Si'*, Encyclical letter on care for our common home, June 18, 2015; Daniel Burke, "Pope Francis: 'Revolution' Needed to Combat Climate Change," *CNN.com*, June 18, 2015.

49. William Quigley, "The Living Wage And Catholic Social Teaching," *America: The National Catholic Review,* August 28, 2006.

50. Robert Wilde, "Climate Expert: Marxists, Global Warming Extremists Control Vatican," Breitbat.com, June 13, 2015; Rush Limbaugh, "The Pope's Leaked Marxist Climate Rant [transcript]," *Rushlimbaugh.com*, June 16, 2015; Denise Robins, "Conservative Media v. the Pope: The Worst Reactions to Pope Francis' Climate Change Encyclical," *Media Matters,* June 18, 2015.

51. Joseph Heath, "The Pope's Climate Error," *New York Times,* June 20, 2015.

52. The *New York Times* ran front page and major stories five days in a row.

53. Anderson, "Thomas Paine's 'Agrarian Justice,'" 14.

54. Quigley, "The Living Wage."

55. Francis, *Laudato Si'*, 139.

56. Ibid., 84.

57. Ibid., 39.

CHAPTER 4

1. A definition of an innovation system geared to empirical analysis of systems that covers the main features of the system discussed in these comments can be found in Anna Bergek et al., "Analyzing the Dynamics and Functionality of Sectoral Innovation Systems—A Manual." Dynamics of Industry and Innovation: Organizations, Networks and Systems, Copenhagen, 2005, 4, 8, "the goal of an innovation system is to develop, diffuse and utilize innovations. Taking a system approach implies that there is a system with related components (actors, network, institutions). . . . The contribution of a component or set of components to the overall goal is here referred to as a 'function.'"

2. Figure 3.1 is drawn from the following sources: Vijay Mahajan, Eitan Muller, and Frank M. Bass, "New Product Diffusion Models in Marketing: A Review and Directions of Research," *Journal of Marketing* 54 (1990); Rick Brown, "Managing the 'S' Curves of Innovation," *Journal of Consumer Marketing* 7 (1992); Jackie Fenn, *When to Leap on the Technology Hype Cycle*, Gartner Group, 1995; Paul Gilder and Gerard J. Tellis, "Will It Ever Fly? Modeling the Takeoff of Really New Consumer Durables," *Marketing Science* 16 (1997); Paul Gilder and Gerard J. Tellis, "Growing, Growing, Gone: Cascades, Diffusion, and Turning Points in the Product Life Cycle," *Marketing Science* 23 (2004); Rajeev Kohli, Donald R. Lehmann, and Jae Pae, "Extent and Impact of Incubation Time in New Product Diffusion," *Journal of Product Innovation Management* 16 (1999);

Yshitaka Osawa and Kumiko Miazaki, "An Empirical Analysis of the Valley of Death: Large Scale R&D Project Performance in a Japanese Diversified Company," *Asian Journal of Technology Innovation* 14 (2006); Ashish Sood et al., "Predicting the Path of Technological Innovation: SAW vs. Moore, Bass, Gompertz and Kryder," *Marketing Science* 31 (2012).

3. Jayati Sarkar, "Technological Diffusion: Alternative Theories and Historical Evidence." *Journal of Economic Surveys* 12 (1998): 167.

4. Osawa and Miazaki, "The Valley of Death."

5. Gartner Group, *Interpreting Technology Hype* (Stamford, CT: Gartner, Inc., 2013).

6. Brown, "Managing the 'S' Curves," 65.

7. Gilder and Tellis, "Will It Ever Fly?," 267.

8. Ibid. Technological change, product quality, relative advantage of the product. New products, substitute products, availability of complementary products that increase the utility of the new product, and the number of competitors.

9. Ibid.

10. Ibid., 263–264. These authors conclude that "Individual level diffusion models or models that combine economic and communications elements seem especially promising," pointing to a number of studies including Rabikar Chatterjee and Jehoshua Eliashberg, "The Innovation Diffusion Process in a Heterogeneous Population: A Micromodeling Approach," *Management Science* 36 (1990); Dan Horksy, "A Diffusion Model Incorporating Product Benefits, Price, Income and Information," *Management Science* 9 (1990); James M. Lattin and John H. Roberts, *Modeling the Role of Risk-Adjusted Utility in the Diffusion of Innovation*, Working Paper 1019, Graduate School of Business, Stanford University, CA, 1989. Brown, "Managing the 'S' Curves," 73.

11. Brown, "Managing the 'S' Curves", 62.

12. Mahajan, Muller, and Bass, "New Project Diffusion Models," 6–7.

13. Ibid.

14. Sarkar, "Technological Diffusion," 132.

15. Gerd Gigerenzer and Wolfgang Gaissaeir, "Heuristic Decision Making," *Annual Review of Psychology* 62 (2011): 453.

16. However, stepping back from the assumption of perfect rationality can lead to an overemphasis on the irrational, or error in decision making. Ulrich Hoffrage and Torsten Reimer, "Models of Bounded Rationality: The Approach of Fast and Frugal Heuristics," *Management Review* 15 (2004): 456: "[H]euristics were invoked as explanation for systemic errors found in human reasoning – mainly deviation from the laws of probability. Although Tversky and Kahneman repeatedly asserted that heuristics sometimes succeed and sometimes fail, they and many of their colleagues focused on the latter category and interpreted their experimental findings as indicating some kind of fallacy."

17. Hoffrage and Reimer, "Models of Bounded Rationality," 456, "Fast and frugal heuristics, in contrast, are not associated with the value-laden term bias. On the contrary, by taking advantage of the structure of information in the environment, these heuristics can lead to accurate and useful inferences; hence they do not necessarily lead to biases but they can "make us smart." Gigerenzer and Gaissmaier, "Heuristic Decision Making," 473 (quoting James March): "[I]f behavior that apparently deviates from standard procedures of calculated rationality can be shown to be intelligent, then it can plausibly be argued that models of calculated rationality are deficient not only as descriptors of human behavior but also as guides to intelligent choice."

18. Gigerenzer and Gaissmaier, "Heuristic Decision Making," 457–458.

19. Hoffrage and Reimer, "Models of Bounded Rationality," 442, cited in Jörn Sebastian Basel and Rolf Brühl, *Concepts of Rationality in Management Research: From Bounded*

Rationality to Ecological Rationality, ESCP Europe Working Paper No. 57, 2011, 17-1; Hoffrage and Reimer, "Models of Bounded Rationality," 443.

20. Hoffrage and Reimer, "Models of Bounded Rationality," 437, "From such a perspective it is straightforward to study the adaptation of mental and social strategies to real-world environments rather than compare strategies to the norms of probability theory (e.g., *Bayes's rule*, which can be used to update prior beliefs in the light of new data) and logic (e.g., the *conjunction rule* [])]. . . Rather, the performance of a heuristic is evaluated against a criterion that exists in the environment—the distinction between internal consistency versus external correspondence."

21. Basel and Bruhl, "Concepts of Rationality," 19.

22. Luc Soete, Bart Verspagen, and Bas ter Weel, "Systems of Innovation," in *Handbook of the Economics of Innovation* (Volume 2), ed. Bronwyn H. Hall and Nathan Rosenberg (Amsterdam, The Netherlands: North-Holland, 2010), 1163, 1177. "The NSI [National System of Innovation] concept represented for policymakers an alternative to industrial policies, while at the same time providing strong support for the role of public authorities in creating the 'right' institutional conditions for a knowledge-driven economy to flourish. . . . The central idea in modern innovation systems theory is the notion that what appears as innovation at the aggregate level is in fact the result of an interactive process that involves many actors at the micro level, and that next to market forces many of these interactions are governed by nonmarket institutions. Because the efficiency of this process observed at the macro level depends on the behavior of individual actors, and the institutions that govern their interaction, coordination problems arise. . . . Not surprisingly, economists in the institutional tradition of innovation studies and scholars of evolutionary theories became the strongest proponents of the notion of systems of innovation. In these views the system of innovation is a continuous process where institutions (habits and practices), learning, and networks play a central role in generating innovation and technological change . . . the innovation systems literature has led to five main insights: the importance of a broader set of innovation inputs than just R&D, the importance of institutions and organizations, the role of interactive learning, leading to a dynamic perspective rather than a static allocative one, the role of interaction between agents, and, finally, the role of social capital. Each one of those specific points opens up links with literatures and approaches that are not so common in (mainstream) economics."

23. M. P. Hekkert et al., "Functions of Innovation Systems: A New Approach for Analyzing Technological Change," *Technological Forecasting and Social Change* 74 (2007): 426. "A common trigger for virtuous cycles . . . is guidance of the search. In this case societal problems are identified and government goals are set. . . . These goals lead to new resources, which, in turn, lead to knowledge development and increasing expectations about technological options (Motor C). Another possible start for virtuous cycles are entrepreneurs who lobby for better economic conditions to make further technology development possible (function 7: counteract resistance to change). They either lobby for more resources to perform R&D which may leaded to higher expectations (Motor B), or they lobby for market formation since very often a level playing field is not present (Motor A). When markets are created, a boost in entrepreneurial activities (F1) is often visible leading to more knowledge formation (F2), more experimentation (F1), and increased lobby (F7) for even better conditions and high expectations [F3] that guide further research (F4)."

24. Pradhan et al., "Economic Growth and the Development of Telecommunications Infrastructure in the G-20 Countries: A Panel-VAR Approach," *Telecommunications Policy* 38 (2014): 634; Rudra P. Pradhan, Mak B. Arvin, and John H. Hall, "Economic Growth, Development of Telecommunications Infrastructure, and Financial Development in Asia, 1991–2012," *The Quarterly Review of Economics and Finance,* 59 (2016): 25–38; The

supply-leading hypothesis (SLH) contends that telecommunications infrastructure is a necessary pre-condition to economic growth. Thus, the causality runs from DTI to economic growth. The proponents of this hypothesis are (Andrzej Cieslik and Magdalena Kaniewska, "Telecommunications Infrastructure and Regional Economic Development: The Case of Poland," *Regional Studies* 38 [2004]; Lars-Hendrik Roller and Leonard Waverman, "Telecommunications Infrastructure and Economic Development: A Simultaneous Approach," *American Economic Review,* 91 [1996]) maintain that the telecommunications infrastructure induces economic growth by directly supporting other infrastructures and factors of production, thereby improving economic growth. The second proposition is the demand-following hypothesis (DFH), which suggests that causality runs instead from economic growth to telecommunications infrastructure. Supporters of the demand-following hypothesis suggest that telecommunications infrastructure plays only a minor role in economic growth: it is merely a byproduct or an outcome of economic growth (Richard O. Beil, George S. Ford, and John D. Jackson, "On the Relationship Between Telecommunications Investment and Economic Growth in the United States," *International Economic Journal* 19 [2005]). The idea is that as an economy grows, an additional telecommunications infrastructure emerges in the economy.

25. The argument has been most forcefully argued for digital communications networks. Md. Shahidduzzaman, "The Long-Run Impact of Information and Communication Technology on Economic Output: The Case of Australia," *Telecommunications Policy* 38 (2014), shows that the contribution to economic growth for telecommunications is six times as large as its share of capital investment. Pradhan, Arvin, and Hall, "Economic Growth," 636, also cites others who support this hypothesis (Chakraborty & Nandi, "Main Line Telecommunications Infrastructure, Levels of Development and Economic Growth: Evidence from a Panel of Developing Countries," *Telecommunications Policy* 35 [2011]).

26. Carlota Pérez, "Technological Dynamism and Social Inclusion in Latin America: A Resource-Based Production Development Strategy," *CEPAL Review* 100 (2010), 124.

27. Carlota Pérez, *Technological Revolutions and Techno-Economic Paradigms*, Working Papers in Technology Governance and Economic Dynamics, January 2009, 18; Carlota Pérez, "Financial Bubbles, Crises and the Role of Government in Unleashing Golden Ages," in *Innovation and Finance*, ed. A. Pyka and H. P. Burghof (London: Routledge, 2013).

28. Pérez, "The Financial Crisis," 1.

29. Rainer Kattel, Wolfgang Dreschler, and Erik S. Reinart, "Introduction: Carlota Perez and Evolutionary Economics," in *Techno-Economic Paradigms: Essays in Honour of Carlota Perez*, ed. Wolfgang Dreschler, Rainer Kattel, and Erik S. Reinart (London: Anthem Press, 2011), 8.

30. Mark Cooper, "Small Modular Reactors and the Future of Nuclear Power in the United States," *Energy Research & Social Science* 3 (2014), describes the declining cost.

31. Carlota Pérez, *Technology Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages* (Northampton, MA: Elgar Publishing, 2002),42.

32. Pérez, *The Advance of Technology*, 2.

33. Pérez, "Technological Dynamism," 135.

34. Pérez, *The Advance of Technology*, 2.

35. Pérez, "Technological Dynamism," 124.

36. Pérez, *Technological Revolutions*, 155–156.

37. Franco Malerba, *Industrial Dynamics and Innovation: Progress and Challenges*, Presidential Address, 32nd Conference of the European Association for Research in Industrial Economics, September 1–4, 2005, 77. Until the advent of the internet, the telecom

service industry did not experience major technological and market discontinuities. With the internet and its open network architecture, modular components, and distributed intelligence, both the knowledge base and the types of actors and competencies have changed significantly.

38. Wesley M. Cohen, "Fifty Years of Empirical Studies of Innovative Activity and Performance," in *Handbooks of the Economics of Innovation* (Volume 1), ed. Bronwyn H. Hall and Nathan Rosenberg (Amsterdam, The Netherlands: North-Holland, 2010), 172. "All of the sources of ideas for new R&D projects outside the R&D lab itself, including suppliers, rivals, university and government labs or even a firm's own manufacturing operations, customers are far and away the most important."

39. Cohen, "Fifty Years," 172.

40. Shane Greenstein, "Innovative Conduct in Computing and Internet Market," in *Handbook of the Economics of Innovation* (Volume 1), ed. Bronwyn H. Hall and Nathan Rosenberg (Amsterdam, The Netherlands: North-Holland, 2010), 489–490.

41. Cohen, "Fifty Years," 158. "[O]ne might usefully distinguish among the sources on the basis of the degree to which they are tied to specific firms (e.g., learning by doing, or R&D fixed cost spreading), versus those which are tied to technologies that can potentially stand apart from the firms that may have first introduced them (e.g., network externalities or learning by using). In this latter case, the nature of the innovation, and possibly its complementarity with other technologies, will tend to drive market structure rather than the reverse."

42. Usha C. V. Haley and Douglas A. Schuler, "Government Policy and Firm Strategy in the Solar Photovoltaic Industry," *California Management Review* 54 (2011),17.

43. Rosalie Ruegg and Patrick Thomas, *Linkages from DOE's Wind Energy Program R&D to Commercial Renewable Power from Solar Energy* (Washington, DC: U.S. Department of Energy, 2011).

44. Albert N. Link, *Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Combustion R&D Investments: Impacts of a Cluster of Energy Technologies* (Washington, DC: U.S. Department of Energy, 2010); Sam Baldwin and Jeff Dowd, "Energy Efficiency and Renewable Energy Challenges, Opportunities, Impacts," Keynote Presentation at Understanding Federal R&D Impact, Thomson-Reuters, Washington, DC, March 19, 2013, 15.

45. R. Margolis, R. Mitchell, and K. Zweibel, *Lessons Learned from the Photovoltaic Manufacturing Technology/PV Manufacturing R&D and Thin-Film PV Partnership Projects*, Technical Report NREL/TP-520-39780, September, 2006; Rosalie Ruegg and Patrick Thomas, *Linkages from DOE's Solar Photovoltaic R&D to Commercial Renewable Power from Solar Energy* (Washington, DC: U.S. Department of Energy, 2009); Ruegg and Thomas, *DOE's Solar Photovoltaic R&D*; Hopkins, *The Making of a Champion or, Wind Innovation for Sale: The Wind Industry in the United States, 1980–2011*, AIR Working Paper #13-08/02 (Cambridge, MA: Academic-Industry Research Network, 2013); Ryan Wiser, *A Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards*, Technical Report, NREL TP-6A20-65005, January 2016.

46. See Link, *Retrospective Benefit-Cost Evaluation*; Baldwin and Dowd, "Energy Efficiency"; and below, Part IV.

47. Pérez, *Technological Revolutions*.

48. Acemoglu and Robinson, *Why Nations Fail*.

49. Cooper, "Why Growing Up Is Hard to Do."

50. For example, the Mercatus Center (Veronique De Rugy, *Renewable-Energy Subsidies and Electricity Generation*, Mercatus Center, George Mason University, May 21, 2013), a market fundamentalist think tank that will be discussed in Chapter 6, uses statistical tricks to present a distorted picture of subsidies; first, it focuses on a single year, rather than

the lifecycle for its primary comparison. Second, when it does offer a lifecycle view, it gives only wind, not the lifecycle subsidies of the central station resources. Third, it truncates the pay-off period, by looking at current output, when the overwhelming majority of the benefits for wind are yet to come.

CHAPTER 5

1. Very long-lived hydro facilities might be an exception, although refurbishing and updating of these projects would be necessary.

2. https://en.wikipedia.org/wiki/Merit_order, "The merit order is a way of ranking available sources of energy, especially electrical generation, based on ascending order of price (which may reflect the order of their short-run marginal costs of production) together with the amount of energy that will be generated. In a centralized management, the ranking is so that those with the lowest marginal costs are the first ones to be brought online to meet demand, and the plants with the highest marginal costs are the last to be brought on line. Dispatching generation in this way minimizes the cost of production of electricity. Sometimes generating units must be started out of merit order, due to transmission congestion, system reliability or other reasons."

3. In analyses that impose environmental constraints on resource selection this is sometimes referred to as the "funding order" (see Erin Baker, *Uncertainty, Technical Change and Policy Models*, University of Massachusetts–Boston, College of Management, July 2007).

4. The levelized cost is adjusted to reflect the decline in gas costs between 2013 and 2015 used by Lazard.

5. In the case of Vogtle, additional potential cost estimates of another 50 percent have surfaced. This would put Vogtle costs close to Hinkley. Southern Alliance for Clean Energy, "Plant Vogtle's Price Tag Climbs to $21 Billion as Commission Experts Predict Further Delays and Cost Increases for Southern Company's Proposed Reactors," *Cleanenergy .org*, December 11, 2015; Walter C. Jones, "Georgia Power Adding Up Costs of Vogtle Delay," *Athens Banner Herald*, February 14, 2015.

6. A more recent estimate for Vogtle is 93 percent of the cost of Hinkley. The cost increase in Nuclear Intelligence Weekly puts overnight cost of Vogtle at $1,000 above Lazard's high estimate, which adds about $13/MWh, to put Vogtle at $140/MWh. However, since we are using Lazards' 2015 projections as a base, we conduct the analysis with that figure and include Hinkley and North Anna as separate data points.

7. For the purposes of this analysis to maintain consistency with the underlying Lazard cost projections, I use estimates of the overnight cost (Sean Farrell and Terry Macalister, "Work to Begin on Hinkley Point Reactor Within Weeks after China Deal Signed," *The Guardian*, October 13, 2015; Scott Norwood, Direct Testimony of Scott Norwood on Behalf of the Office of the Attorney General, Division of Consumer Counsel, Virginia Electric and Power Company, Integrated Resource Plan Filing Pursuant to Va. Code § 56-597 et. Seq., Case No. PUE-2015-00035, September 15, 2015, 5) to calculate the capital cost per kW, and then derive the levelized cost by multiplying the high end of the Lazard nuclear range: LCOE = (Project $/kW/Lazard High $/kW) * Lazard high LCOE. 1 British £ to U.S. $ at 1.6. Hinkley overnight costs are $9,000/kW (although cost escalation to $10,000 is already being mentioned). North Anna overnight costs are $10,186/kW.

8. Electric Power Research Institute, *Australian Power Generation Technology Study* (Palo Alto, CA: EPRI, 2015).

9. Cooper, "Small Modular Reactors."

10. Mark Cooper, "Nuclear Safety and Affordable Reactors: Can We Have Both?" *Bulletin of the Atomic Scientists* 68 (2012); Cooper, "Small Modular Reactors," discusses the long-term trend in relation to the recent release and analysis of the French nuclear cost data.

11. https://en.wikipedia.org/wiki/Overnight_cost: "Overnight cost is the cost of a construction project if no interest was incurred during construction, as if the project was completed 'overnight.' The overnight cost is frequently used when describing power plants. The unit of measure typically used when citing the overnight cost of a power plant is $/kW. For example, the overnight cost of a nuclear plant might be $5,000/kW, so a 1000 MW plant would have an overnight cost of $5 billion. (Interest on the $5 billion spent during construction would be extra.)"

12. Lazard, "Lazard's Levelized Cost," 13, 14.

13. EPRI, *Australian Power Generation Technology Study*, 2015.

14. S. Jaffe and K. A. Adamson, *Advanced Batteries for Utility-Scale Energy Storage* (Boulder, CO: Navigant Consulting, 2014).

15. As reported in Michael Fuhs, "Forecast 2030: Stored Electricity at $0.05/kWh," *PV World,* September 29, 2014.

16. Lazard, "Lazard's Levelized Cost."

17. International Renewable Energy Agency, *Battery Storage for Renewables: Market Status and Technology Report* (Abu Dhabi, UAE: IRENA, 2015); Peter Bronski, et al., *The Economics of Grid Defection: When and Where Distributed Solar Generation Plus Storage Competes with Traditional Utility Service* (Boulder CO: RMI, 2014); Giles Parkinson, "Citigroup: Solar + Battery Storage 'Socket' Parity in Years," *RenewEconomy*, October 3, 2014; Garrett Fitzgerald, *The Economics of Battery Energy Storage: How Multi-Use, Customer-Sited Batteries Deliver the Most Services and Value to Customers and the Grid* (Boulder, CO: Rocky Mountain Institute, 2015); Peter Bronski et al., *The Economics of Demand Flexibility: How "Flexwatts" Create Quantifiable Value for Customers and the Grid* (Boulder, CO: Rocky Mountain Institute, 2015).

18. Julien Dumoulin-Smith, et al., *US Solar & Alternative Energy: The Real Battery Storage Opportunity* (Zurich, Switzerland: UBS, 2015); T. R. Ayodele and A. S. O. Ogunjuyigbe, "Mitigation of Wind Power Intermittency: Storage Technology Approach," *Renewable and Sustainable Energy Reviews* 44 (2015); Peter Bronski, *The Economics of Load Defection: How Grid-Connected Solar-Plus Battery Systems Will Compete with Traditional Electric Service, Why It Matters, and Possible Paths Forward* (Boulder, CO: Rocky Mountain Institute, 2015); Fitzgerald et al., *The Economics of Battery Energy Storage*.

19. Cooper, "Nuclear Safety."

20. Cooper, "Small Modular Reactors."

21. Joachim Seel, Galen Barbose, and Ryan Wiser, *Why Are Residential PV Prices in Germany So Much Lower Than in the United States? A Scoping Analysis*, U.S. Department of Energy, SunShot Webinar, February 26, 2013.

22. David Richard Walwyn and Alan Colin Brent, "Renewable Energy Gathers Steam in South Africa," *Renewable and Sustainable Energy Reviews* 41 (2015): 390–401.

23. Dan Eggers, Kevin Cole, and Matthew Davis, *Nuclear . . . The Middle Age Dilemma? Facing Declining Performance, Higher Costs, Inevitable Mortality*, Credit Suisse, 2013, 1.

24. William H. Golove and Joseph H. Eto, *Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency,* Report LBL-38059, Lawrence Berkeley Laboratory, 1996.

25. Kenji Takahashi and David Nichols, *The Sustainability and Cost of Increasing Efficiency Impacts: Evidence from Experience to Date*, ACEEE Summer Study on Energy Efficiency in Buildings, 2008.

26. Roland Hwang and Matt Peak, *Innovation and Regulation in the Automobile Sector: Lessons Learned and Implications for California's CO_2 Standards*, Working Paper, April, 2006.

27. Winston Harrington, *Grading Estimates of the Benefits and Costs of Federal Regulation: A Review of Reviews* (Washington, DC: Resources for the Future, 2006), 3; Winston Harrington, Richard Morganstern, and Peter Nelson, *How Accurate Are Regulatory Cost Estimates* (Washington, DC: Resources for the Future, 2010).

28. Kate Whitefoot, Meredith Fowlie, and Steven Skerlos, *Product Design Response to Industrial Policy: Evaluating Fuel Economy Standards Using an Engineering Model of Endogenous Product Design*, Working Paper, Energy Institute at Haas, May 2012, 1–5. "We perform counterfactual simulation of firms' pricing and medium-run design responses to the reformed CAFE regulation. Results indicate that compliant firms rely primarily on changes to vehicle design to meet the CAFE standards, with a smaller contribution coming from pricing strategies designed to shift demand toward more fuel-efficient vehicles. . . . Importantly, estimated costs to producers of complying with the regulation are three times larger when we fail to account for tradeoffs between fuel economy and other vehicle attributes."

29. While traditional studies of the cost of saved energy reach a strong consensus, other strands in the literature and factors should be considered. A review by LBNL of utility programs (Ian M. Hoffman, et al., *The Total Cost of Saving Electricity Through Utility Customer-Funded Energy Efficiency Programs: Estimates at the National, State, Sector and Program Level*, Policy Brief, Lawrence Berkeley Laboratory, 2015) adds in the administrative costs and yields some results in the range of $0.05/kWh for the residential sector. Since these estimates include administrative costs of programs that involve significant interventions to stimulate uptake, they may not be comparable to the resource cost estimates discussed earlier. In fact, simple rebate programs are very low in cost. Assumptions about discount rates may also contribute to the higher estimates. The finding about rebate programs points to another important consideration. The utility-based analysis does not include other lower-cost approaches, like appliance efficiency standards, building codes and combined heat and power projects. These can significantly reduce energy consumption without the heavy implementation costs of utility programs.

30. Steven Nadel and Andrew Delaski, *Appliance Standards: Comparing Predicted and Observed Prices*, Research Report E13D, ACEEE, 2013; R. Sauter and A. Volkery, *Review Of Costs and Benefits of Energy Savings: Task 1 Report 'Energy Savings 2030'* (Brussels, Belgium: Institute for European Environmental Policy, 2013), 9.

31. Mark Cooper, "From Wifi to Wikis and Open Source: The Political Economy of Collaborative Production in the Digital Information Age," *Journal on Telecommunications and High Technology Law* 5 (2006).

32. Cooper, *Power Shift*.

33. Cooper, "Small Modular Reactors."

34. Based on Jacobson et al., *Roadmaps for 139 Countries*. See text for a discussion of the data and methodologies. BAU = Business as Usual.

35. Ibid.; Jordan Macknick, *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*, Technical Report NREL/TP-6A20-50900, NREL, 2011.

36. Cooper, "Nuclear Safety."

37. Vasilis Fthenakis and Hyung Chul Kim, "Life-Cycle Uses of Water in U.S. Electricity Generation," *Renewable and Sustainable Energy Review* 14 (2010).

38. Mark Z. Jacobson, "Review of Solutions to Global Warming, Air Pollution, and Energy Security," *Energy and Environmental Science* 2 (2009); Saeed Hadian and Kaveh Madani, "A System of Systems Approach to Energy Sustainability Assessment: Are All Renewables Really Green?" *Ecological Indicators* 52 (2015).

39. Munish K. Chandel, Lincoln F. Pratson, and Robert B. Jackson, "The Potential Impacts of Climate-Change Policy on Freshwater Use in Thermoelectric Power Generation," *Sustainability of Biofuels* 39 (2011); Anna Pechan and Klaus Eisenack, "The Impact of Heat Waves on Electricity Spot Markets," *Energy Economics* 43 (2014).

40. In addition to the recent U.S. analysis by U.S. EPA/NHTSA, *In the Matter of Notice of Upcoming Joint Rulemaking to Establish 2017 and Later Model Year Light Duty Vehicle GHG Emissions and CAFE Standards*, Docket ID No. EPA-HQ-OAR-0799 Docket ID No. NHTSA-2010-0131, 2011, see Jamie Howland, et al., *Energy Efficiency: Engine of Economic Growth* (Rockport, ME: Environment Northeast, 2009) and New York State Energy Research & Development Authority, *Macro-Economic Impact Analysis of New York's Energy Efficiency Programs: Using REMI Software* (Albany NY: NYSERDA, August 4, 2011), for individual states; Ingrid Holmes and Rohan Mohanty, *The Macroeconomic Benefits of Energy Efficiency: The Case for Public Action* (London: E3G, 2012) and Cambridge Centre for Climate Mitigation Research, *The Macro-Economic Rebound Effect and the UK Economy* (Cambridge, U.K.: Cambridge Econometrics and Policy Studies Institute, May 2006) and Lisa Ryan and Nina Campbell, *Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements*, Insight Series (Paris, France: International Energy Agency, 2012) for a general global review.

41. Jennifer Amann, *Valuation of Non-Energy Benefits to Determine Cost-Effectiveness of Whole-House Retrofit Programs: A Literature Review*, American Council for an Energy Efficient Economy, May 2006.

42. Ibid.

43. Mihály Dombi, István Kuti, and Péter Balogh, "Sustainability Assessment of Renewable Power and Heat Generation Technologies," *Energy Policy* 67 (2014); Alexandru Maxim, "Sustainability Assessment of Electricity Generation Technologies Using Weighted Multi-Criteria Decision Analysis," *Energy Policy* 65 (2014).

44. Pechan and Eisenach, "Heat Waves."

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46. Bengt Johansonn, "Security Aspects of Future Renewable Energy Systems: A Short Overview," *Energy* 61 (2013).

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CHAPTER 6

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46. Mills and Wiser, *Strategies for Mitigating*, 17

47. Ibid., 29.

48. The LBNL study shows the ratio as high as 3-to-1, and cites (p. 14) a similar study for ERCOT, which put the ratio at 2.33-to-1. Other studies have arrived at ratios that favor solar, when that resource is richer.

49. Mills and Wiser, *Strategies for Mitigating*, 19.

50. Ibid., 24, "A portfolio with high geographic diversity leads to a higher value of wind due to a reduction in extremes: fewer hours have significant amounts of wind from all wind sites in the portfolio (reducing overgeneration and curtailment), and more hours have at least a small amount of wind generation from some sites. The benefit of increased geographic diversity is more pronounced with high wind penetration levels since wind is more likely to affect wholesale prices at high penetration levels."

51. Ibid., 25, "The increase in the capacity value of wind with 10% PV is due to PV shifting the timing of the peak prices into the early evening, when wind generation is somewhat stronger"; 27, "As PV penetrations increase, adding 10% wind increases the marginal value of PV substantially relative to the Reference scenario. . . . The increase in the capacity value is tied in part to wind generation occurring."

52. Ibid., 33, "The increase in the value of PV with low-cost storage is almost entirely due to the increase in the energy value of PV relative to the Reference scenario. . . . The energy value of PV increases in part due to a reduction in PV curtailment from 2.9% with 30% PV in the Reference scenario to less than 0.1% in the Low-cost Storage scenario. The strong negative correlation between PV generation and generation from storage (existing and new) at high PV penetrations indicates storage is consistently charging when PV is generating and discharging otherwise."

53. Ibid., 32, 33.

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55. Ibid., 35, "since reductions in demand relative to historical levels at time of system need enable a balance between demand and generation rather than relying on new conventional capacity."

56. In Mills and Wiser, *Strategies for Mitigating*, the issue enters implicitly through the frequent attention to forecasting error. The other major studies give sub-hourly scheduling prominent, explicit attention.

57. Ibid., 43.

58. Ibid., 30, "In addition, the impact of more-flexible generation will depend on the degree of flexibility in the existing generation mix. California has significant amounts of CTs, PHS capacity, and hydropower. In comparison, we found in an earlier analysis of highly concentrated wind in the Rocky Mountain Power Area [Andrew Mills and Ryan Wiser, *Solar Valuation in Utility Planning Studies*. Clean Energy States Alliance: RPS Webinar, January 2013] that assuming all new CCGTs had quick-start capability increased the value of wind by up to $6/MWh at 30% wind penetration. The Rocky Mountain Power Area has much less flexible incumbent generation relative to California."

59. Ibid., 39.

60. E3, *Higher Renewables Portfolio Standard*, 129.

61. Ibid., 29.

62. Ibid., 19.

63. Mills and Wiser, *Strategies for Mitigating*, put costs in the $5-$10/MWh range; Andrew Mills and Ryan Wiser, *Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power*, Lawrence Berkeley National Laboratory, 2010, 2. "We conclude that the costs of managing the short-term variability of PV are dramatically reduced by geographic diversity and are not substantially different from the costs for managing the short-term variability of similarly sited wind in this region." Michael Milligan et al., "Wind Power Myths Debunked: Common Questions and Misconceptions," *IEEE Power & Energy Magazine*, (2009), 93. "The incremental balancing costs caused by wind are 10% or less of the wholesale value of the wind power. . . . The experience of countries and regions that already have quite a high wind penetration (from 5% to 20% of gross electric energy demand) has been that there existing reserves are deployed more often after wind power is added to the system, but no additional reserve capacity is required."

64. Mills and Wiser, *Strategies for Mitigating*, 36–37.

65. Ibid., 31.

66. U.S. Department of Energy, *Wind Vision*.

67. The four "least regrets" opportunities identified in this study include: "1. Increase regional coordination. . . . 2. Pursue a diverse portfolio of renewable resources. . . . 3.

Implement a long-term, sustainable solution to address overgeneration before the issue becomes more challenging. . . . 4. Implement distributed generation solutions. . . . 5. Promising technologies, storage (Solar thermal with energy storage, Pumped storage, Other forms of energy storage including battery storage, Electric vehicle charging, Thermal energy storage). . . . 6. Flexible loads that can increase energy demand during daylight hours (Advanced demand response and flexible loads). . . . 7. Sub-five minute operations. . . . 8. Size of potential export markets for excess energy from California. . . . 9. Transmission constraints. . . . 10. Changing profile of daily energy demand. . . . 11. Future business model for thermal generation and market design. . . . 12. Optimal thermal generation fleet under high RPS" (pp. 31–35).

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70. Eichman, "Exploration of the Integration of Renewable Resources into California's Electric System Using the Holistic Grid Resource Integration and Deployment (Hi-GRID) Tool," *Energy* 50 (2013); Sarah Becker et al., "Features of a Fully Renewable US Electricity System: Optimized Mixes of Wind and Solar PV and Transmission Grid Extensions," *Energy* 72 (2014); Sarah Becker et al., "Transmission Grid Extensions During the Build-Up of a Fully Renewable Pan-European Electricity Supply," *Energy* 64 (2014).

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91. The Smart Grid is at the classic turning point in early diffusion and in need of social support to overcome concerns and attitudinal barriers grounded in the real world experience of consumers. Joeri Naus et al., "Smart Grids, Information Flows and Emerging Domestic Energy Practices," *Energy Policy* 68 (2014), 436: "Smart grids generate three key new information flows that affect social relations. Practice theory can reveal the ways in which households handle/govern information. Householders show ambivalence about the workings of the different information flows. Policies should account for the 'bright' as well as the 'dark' sides of information." Chan-Kook Park, Hyun-Jae Kim, and Yang-Soo Kim, "A Study of Factors Enhancing Smart Grid Consumer Engagement," *Energy Policy* 72 (2014), 211: "We examine what factors influence electricity consumers' smart grid acceptance. We test the smart grid technology acceptance model including the perceived risk as a main factor. The importance of consumer education and public relations of the smart grid has been confirmed. Another short cut to ensure the acceptance of the smart grid is to mitigate the anxiety about the risk in the use of the Smart grid." Pepermans, "Valuing Smart Meters," *Energy Economics* 45 (2014); Guizhou Ren, Guoqing Ma, and Ning Cong, "Review of Electrical Energy Storage System for Vehicular Applications," *Renewable and Sustainable Energy Reviews* 41 (2015).

92. Both in its interaction with smart grid and directly in transforming production and distribution processes. Mohana Ravindranath, "At GSA, an 'Internet of Things' Experiment," *Washington Post*, August 31, 2014; Owen Poindexter, "The Internet of Things Will Thrive on Energy Efficiency," *Government Technology*, July 29, 2014; W. David Stephenson, "Internet of Things Could Offset Government Inaction on Climate," *Greenbiz.com*, November 17, 2014.

93. Solar as both baseload resources (e.g. Stefan Pfenninger et al., "Potential for Concentrating Solar Power to Provide Baseload and Dispatchable Power," *Nature Climate Change* 4 [2014]) and a distributed resource (rooftop PV).

94. U.S. Department of Energy, *Wind Vision*, xv.

95. Shrimali, Lynes, and Indvik, "Wind Energy Deployment," 454. "The complementary characteristic of battery (large energy density for long term storage, but low power density, low charge and discharge efficiency) and super-capacitor (low energy density, but high power density, fast charge and discharge rate) has . . . revealed that, the hybrid of the duo can optimize the battery charge and discharge process, thereby . . . can extend system lifetime by 62% and reduce the cost of energy storage system by 41%. . . . A suitable energy storage device combined with wind turbines, can firm and shape wind power output, transforming the wind generation into a firm and predictable energy source. . . . However, no single storage technology can meet up with all the criteria. Thus hybrid storage technology is being explored as a potential solution." Allal M. Bouzid et al., "A Survey on Control of Electric Power Distributed Generation Systems for Micro Grid Applications," *Renewable and Sustainable Energy Reviews* 44 (2015), 753: "A micro grid can be defined as a part of the grid consisting of prime energy movers, power electronics converters, distributed energy storage systems, and local loads. This makes the electrical network more flexible and intelligent. Micro grids and virtual power plants (VPPs) are two low voltage distribution network concepts that can participate in active network management of a smart grid. They are becoming an important concept to integrate distributed generation (DG) and energy storage systems."

96. Peerapat Vithayasrichareon, Jenny Riesz, and Iain F. MacGill, "Using Renewables to Hedge Against Future Electricity Industry Uncertainties—An Australian Case Study," *Energy Policy* 76 (2015), 43.

97. Lynette Molyneaux et al., *Australian Power: Can Renewable Technologies Change the Dominant Industry View?* Paper presented at the Australian Solar Energy Society Conference, Melbourne, December 2012.

CHAPTER 7

1. Adam B. Jaffe and Robert N. Stavins, "The Energy Paradox and the Diffusion of Conservation Technology," *Resource and Energy Economics* 16 (1994); Golove and Eto, "Market Barriers." Although the "energy paradox" and "efficiency gap" are used interchangeably, we prefer the energy gap to avoid any confusion with the thoroughly discredited, "Jevon's Paradox," which predicts all energy savings from efficiency will be consumed by increased energy consumption.

2. Electricity and natural gas savings based on Rachel Gold et. al., *Energy Efficiency in the American Clean Energy and Security Act of 2009: Impact of Current Provisions and Opportunities to Enhance the Legislation*, American Council for an Energy Efficient Economy, September 2009; McKinsey & Company, "Unlocking Energy Efficiency"; National Research Council of the National Academies, *America's Energy Future: Technology and Transformation, Summary Edition* (Washington, DC: National Academies Press, 2009).

3. Ted Gayer and W. Kip Viscusi, "Overriding Consumer Preferences with Energy Regulations," *Journal of Regulatory Economics* 43 (2013): 248–264.

4. Ibid., i.

5. Ibid., 37.

6. Ibid., 1.

7. Ibid., 37.

8. Ibid., 38.

9. McKinsey, "Unlocking Energy Efficiency," viii.

10. Steve Sorrell, Alexandra Mallet, and Sheridan Nye, *Barriers to Industrial Energy Efficiency, A Literature Review,* Working Paper, United Nations Industrial Development Organization, 2011, 11

11. Joachim Schleich and Edelgard Gruber, "Beyond Case Studies: Barriers to Energy Efficiency in Commerce and the Services Sector," *Energy Economics* 30 (2008), 1–2. Emphasis added to identify the three main schools of analysis we ultimately adopt to organize the framework. A similar formulation is offered by Patrik Thollander, Jenny Palm, and Patrik Rohdin, "Categorizing Barriers to Energy Efficiency – An Interdisciplinary Perspective," in *Energy Efficiency,* ed. Jenny Palm (InTech, 2010), 3.

12. Carl Blumstein and Margaret Taylor, *Rethinking the Energy-Efficiency Gap: Producers, Intermediaries and Innovation*, Working Paper, Energy Institute at Haas, May 2013, 2.

13. Ted Gayer and W. Kip Viscusi, "Overriding Consumer Preferences," 1.

14. Golove and Eto, "Market Barriers."

15. Ibid., iv.

16. There has recently been a dramatic re-commitment to publicly-sponsored energy efficiency and a substantial increase in allocated resources; Alan H. Sanstad, W. Michael Hanemann, and Maximillion Auffhammer, "End-Use Energy Efficiency in a "Post-Carbon California Economy," in *Managing Greenhouse Gas Emissions in California* (Berkeley, CA: The California Climate Change Center at UC Berkeley, 2006), 5–6.

17. Golove and Eto, "Market Barriers," x.

18. Ibid.

19. Ibid., 22.

20. Ibid., 23.

21. Ibid., 23.

22. Kenneth Gillingham, Richard G. Newell, and Karen Palmer, *Retrospective Examination of Demand-side Energy Efficiency Policies* (Washington, DC: Resources for the Future, 2004), 7.

23. Ibid., 8.

24. Marius Claudy and Aidan O'Driscoll, "Beyond Economics: A Behavioral Approach to Energy Efficiency in Domestic Buildings," *Journal of Sustainable Energy Development* 1 (2008); based on Paul C. Stern, "New Environmental Theories: Towards a Coherent Theory of Environmentally Significant Behavior," *Journal of Social Issues* 56 (2000); see also Charlie Wilson and Hadi Dowlatabadi, "Models of Decision Making and Residential Energy Use," *Annual Review of Environmental Resources* 32 (2007), 183.

25. Nick Wilkinson, *An Introduction to Behavioral Economics* (New York: Palgrave, 2008).

26. Gross et al., *On Picking Winners*.

27. Popp, Newell, and Jaffe, "Energy, the Environment, and Technological Change," 877: "The generation of knowledge through the innovative process contrasts sharply with the negative externalities from pollution. Because of the public goods nature of knowledge, a firm that invests in or implements a new technology typically creates benefits for others while incurring all of the costs. The firm therefore lacks the incentive to increase

those benefits by investing in technology. . . . Technology creates positive externalities, and so the invisible hand of the market produces too little of it."

28. William Nordhaus, "Designing a Friendly Space for Technological Change to Slow Global Warming," *Energy Economics* 33 (2011), 672, 670–671.

29. John P. Weyant, "Accelerating the Development and Diffusion of New Energy Technologies: Beyond the Valley of Death," *Energy Economics* 33 (2011), xx.

30. Ibid., 677.

31. Ibid., 675.

32. Roger Noll, "Comment," *Energy Economics* 33 (2011), 683.

33. Ibid., 685.

34. Acemoglu et al., "The Environment and Dedicated Technical Change," *American Economic Review* 102 (2012), 132.

CHAPTER 8

1. Christine Ammer and Dean S. Ammer, *Dictionary of Business and Economics (Revised and Expanded Edition)* (New York: Free Press, 1984), describe a situation of scarcity that applies well to the peak load problem, noting that "when the supply is exceptionally small—its price will be exceptionally high, and it will be said to have *scarcity value*" (416) and links it to the definition of *quasi-rent,* defined as "a return on capital or labor whose supply is temporarily or permanently fixed, so called to distinguish it from a *real rent,* the return on land (whose supply is always fixed). Pearce, *MIT Dictionary*, 395, applies the concept of absolute scarcity to fossil fuels.

2. Eggers, Cole, and Davis, *Middle Age Dilemma*, 1.

3. Energy Information Administration, *Electricity Annual,* 2015, Table 8.4; NEI *Nuclear Costs in Context,* April 2016; Nuclear Street News Team, "NEI Lays Out the State of Nuclear Power," *Nuclearstreet.com*, February 26, 2014; NEI Operating Cost (Nuclear Street News Team, "NEI Lays Out the State of Nuclear Power," *Nuclearstreet.com*, February 26, 2014); Eggers, Cole, and Davis, *Middle Age Dilemma*, 9; Naureen S. Malik and Jim Poulson, "New York Reactors Survival Tests Pricey Nuclear," *Bloomberg,* January 5, 2015, 2. Quad Cities is based on a $580 million subsidy (Steve Daniels, "Exelon Puts an Opening Price Tag on Nuclear Rescue: $580 Million," *Crains Chicago Business*, September 24, 2014), converted to $25/MWH for output at risk reactors. Illinois Commerce Commission et al., *Response To The Illinois General Assembly Concerning House Resolution 1146*, January 5, 2015, real price increase to break even, plus $11/MWH for capital. Ginna is a New York reactor and Quad Cities is a two-reactor site in Illinois for which Exelon has stated specific revenue increases are needed, although these estimates are shrouded in uncertainty. The Illinois Commerce Commission, *Response*, 29–30, was not given cost data by Exelon, but relied on EIA estimates.

4. The Merit Order Effect has been documented in a number of nations in which renewables have shown strong growth in recent years, demonstrating not only that market clearing prices are lowered, but also that they are lowered by an amount that is larger than any subsidies the resources receive. The result is a net benefit to consumers. See for example, United States: Bob Fagan et al., *The Potential Rate Effects of Wind Energy and Transmission in the Midwest ISO Region*, Synapse Energy Economics, Inc., May 22, 2012; Richard W. Caperton, *Wind Power Helps to Lower Electricity Prices,* Center for American Progress, October 10, 2012; Charles River Associates, *Analysis of the Impact of Cape Wind on New England Energy Prices*, Charles River Associates, February 8, 2010; Canada: Mourad Ben Amor et al., "Influence of Wind Power on Hourly Electricity Prices and GHG (greenhouse

gas) Emissions: Evidence that Congestion Matters from Ontario Zonal Data," *Energy* 66 (2014); Australia: Dylan McConnell et al., "Retrospective Modeling of the Merit-Order Effect on Wholesale Electricity Prices from Distributed Photovoltaic Generation in the Australian National Electricity Market," *Energy Policy* 58 (2013); Iain MacGill, *The Impact of Wind on Electricity Prices in the Australian National Electricity Market,* Centre for Energy and Environmental Markets, June 2013; Melbourne Energy Institute, *The Impact of Distributed Solar Generation on the Wholesale Electricity Market,* June 2013; Ireland: Amy Mahoney and Eleanor Denny, *The Merit Order Effect of Wind Generation in The Irish Electricity Market,* Department of Economics, Trinity College, Dublin, 2011; Denmark: Jesper Munksgaard and Poul Erik Morthorst, "Wind Power in the Danish Liberalized Power Market—Policy Measures, Price Impact and Investor Incentives," *Energy Policy* 36 (2008): 3940–3947; Germany: Frank Sensfuss, Mario Ragwitz, and Massimo Genoese, "The Merit-Order Effect: A Detailed Analysis of the Price Effect of Renewable Electricity Generation on Spot Market Prices in Germany," *Energy Policy* 36 (2008): 3086–3094; Italy: Stefano Clò, Alessandra Cataldi, and Pietro Zoppoli, "The Merit-Order Effect in the Italian Power Market: The Impact of Solar and Wind Generation on National Wholesale Electricity Prices," *Energy Policy* 77 (2015); Spain: Gonzalo Sáenz de Miera, Pablo del Río González, and Ignacio Vizcaíno, "Analysing the Impact of Renewable Electricity Support Schemes on Power Prices: The Case of Wind Electricity in Spain," *Energy Policy* 36 (2008); United Kingdom: Richard Green and Nicholas Vasilakos, "The Economics of Offshore Wind," *Energy Policy* 39 (2011). A separate effect that lowers the market clearing price is the fact that renewables tend to lower the level of concentration of supply, reducing the exercise of market power, Mishra et al., "Mitigating Climate Change"; Paul Twomey and Karsten Neuhoff, "Wind Power and Market Power in Competitive Markets," *Energy Policy* 38 (2010); Franz Wirl, "Taxes Versus Permits as Incentive for the Intertemporal Supply of a Clean Technology by a Monopoly," *Resource and Energy Economics* 36 (2014); Bruce Mountain, *Market Power and Generation from Renewables: The Case of Wind in the South Australian Electricity Market Australian Economic Report: No. 2,* Centre for Strategic Economic Studies Victoria University, Melbourne, June 2012.

5. Malik and Polson, "New York Reactors"; William Opalka, "New York Adopts Clean Energy Standard, Nuclear Subsidy," *RTOinsider,* August 1, 2016; William Opalka, "CES Under Attack on Multiple Fronts in Rehearing Requests," *RTOinsider,* September 5, 2016.

6. Illinois Commerce Commission et al., *Response*.

7. Tom Sanzillo and Cathy Kunkel, *First Energy: A Major Utility Seeks a Subsidized Turnaround,* Institute for Energy Economics and Financial Analysis, October 2014.

8. Bronski et al., *The Economics of Load Defection*, 37.

9. Ibid.

10. Peter J. G. Pearson and Timothy J. Foxon, "A Low-Carbon Industrial Revolution? Insights and Challenges from Past Technological and Economic Transformations," *Energy Policy* 50 (2012), 123–124.

11. Amory B. Lovins and Rocky Mountain Institute, *Reinventing Fire: Bold Business Solutions for the New Energy Era* (Boulder, CO: Rocky Mountain Institute, 2011), 216.

12. Marcus Hildmann, Andreas Ulbig, and Goran Andersson, *Revisiting the Merit-Order Effect of Renewable Energy Sources,* Working Paper, February 11, 2014, show that if baseload facilities could stop acting like baseload facilities, they would fit into the emerging electricity system. "Given base load power plants that have sufficient operational flexibility in terms of fast ramping, start/stop times and minimum operation point requirements, energy-only markets seem to work even for high RES penetration scenarios" (p. 13).

13. The original concept is from Joseph Schumpeter, *The Theory of Economic Development* (Cambridge, MA: Harvard University Press, 1961), and has been greatly expanded and developed in recent widely praised analyses of system change (Pérez, *Technology Revolutions*; and Acemoglu and Robinson, *Why Nations Fail*).

14. Economist Intelligence Unit, *The Cost of Inaction, Recognizing the Value at Risk from Climate Change*, Economist Intelligence Unit Perspectives, 2015.

15. EEI, *Distribution 2020: EEI Fall Boards and Chief Executive Meeting*, September 2012.

16. Andrew Bischof, "Utilities Observer: Distributed Generation," *Morningstar*, February 2014. "Investors beware: Distributed generation (DG) could kill utilities as we know them today. It could take a decade or more in the United States, but . . . technologies such as rooftop solar reduce the value of utilities' century-old centralized networks, and erode their efficient-scale competitive advantage. As more customers adopt DG, utilities' costs to maintain and operate the grid must be spread across a smaller customer base, raising customer rates and increasing the economic incentive to cut the cord. The death spiral ends when investors—equity and credit—are left holding an empty purse of dormant power plants and copper wires. . . .

The electric utilities industry group Edison Electric Institute (EEI) recently identified DG as the largest disruptive threat to utilities' business models and financial health. We agree. Utilities' efficient-scale competitive advantages rely on their centralized network monopolies, but that breaks down when customers become self-sufficient competitors. The cost-of-service regulatory model that allows utilities to earn at least their cost of capital in the long run also breaks down when fewer and fewer customers are bearing the costs of maintaining the centralized network. Ultimately, utilities' earnings will shrink, cash flows will suffer, ROIC [Return on Invested Capital] will fall, and utilities' interest and dividend payments will become less certain."

17. Lorraine Murphy, "The Influence of the Energy Performance Certificate: The Dutch Case," *Energy Policy* 67 (2014); Parker et al., "Bernstein Energy and Power Blast," 3.

18. Peter Kind, *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business*, Edison Electric Institute, January 2013, 1.

19. https://www.nrdc.org/media/2014/140212-0

20. U.S. Department of Energy, *Wind Vision*, 86–87. "Most North American power markets now integrate wind power into their security-constrained unit commitment and security-constrained economic dispatch process, allowing the dispatch of wind plants along with conventional power plants based on current grid conditions and economics. This effectively gets wind into the real-time economic optimization process for running the power system, and in turn, encourages the participation of wind plants in the day-ahead markets. Security-constrained economic dispatch also makes wind dispatchable and economical, allowing some degree of wind-plant output control by the system operator. This allows wind forecasts to become more useful and valuable to wind plant operators, market participants, and system operators, because wind is better integrated into systems and markets."

21. Illinois Commerce Commission, *Response*, 71–72.

22. Ibid., 63. "It is also noteworthy that generating facility owners participating in PJM's Reliability Pricing Model base capacity auctions commit to provide generating capacity three years prior to each delivery year; and the penalties for failing to actually make committed capacity available are steep. In PJM and MISO, generators are required to provide advanced notice of unit deactivations."

23. Ibid., 64.

24. Ibid.

25. Ibid.

26. Ibid. "If the retirement or suspension of the generating unit creates a reliability issue, MISO shall: (1) begin negotiations of a potential System Support Resource ("SSR") Agreement with the owner or operator of the Generation Resource; and (2) use reasonable efforts to hold a stakeholder meeting to review alternatives. The list of alternatives to consider and expeditiously approve include (depending upon the type of reliability concern identified): (i) redispatch/ reconfiguration through operator instruction; (ii) remedial action plans; (iii) special protection schemes initiated upon Generation Resource trips or unplanned Transmission Outages; (iv) contracted demand response or Generator alternatives; and (v) transmission expansions. A Generator alternative may be a new Generator, or an increase to existing Generator capacity."

27. Ibid. "Even if notification of a generation owner's intent to close a generating facility does not trigger any reliability concerns, the closure's actual or anticipated impact on electric energy and capacity prices would provide an incentive for firms to construct replacement generating facilities. It would also lead to an increase in the cost-effectiveness of energy efficiency measures, which would justify additional investment in such measures by retail customers (as well as utilities and government agencies that are subject to mandates to subsidize such measures through energy efficiency programs). Furthermore, it would increase congestion on the transmission system, which could justify the acceleration of transmission system upgrades by RTOs like PJM and MISO. Together, such reactions would expand supply, contract demand, and allow for more efficient utilization of resources, all of which would ameliorate or even overcome the increase in prices due to the closure of the plant by itself. That is, in the long run, the closure of a particular power plant could reduce rather than increase prices, as newer more efficient faculties are introduced to the power grid."

28. Ibid., 37–38, "That is, Exelon's closure of one or more plants can increase market prices and thereby increase the revenues earned by Exelon's other plants. This means Exelon has market power. Thus, even if Exelon's least-profitable plants are at least marginally profitable at the present time and expected to remain so in the future, such market power may provide Exelon with a reason to close one or more of those plants."

29. Ibid., 76. "The reliability modeling in this report focuses on 2018–2019, the first year for which PJM capacity obligations have not been determined. The PJM RPM auction for the 2017–2018 delivery year has cleared at a price lower than the target clearing price, indicating more than the amount of capacity required to meet the reliability standard has cleared the auction. There is most likely time to take other actions prior to a retirement effective in the 2019–2020 delivery year. The 2018–2019 horizon was also used for MISO, both for convenience and because MISO itself has not yet issued warnings about future resource adequacy."

30. Ibid., 73. "This analysis contained in this report demonstrates that there is a potential for impacts on reliability and capacity from the premature closure of the at-risk nuclear plants. However, in many of the cases analyzed, reliability impacts remain below industry standard thresholds, and impacts appear to be more significant in other states than in Illinois. Taken alone, there may not be sufficient concern regarding reliability and capacity to warrant the institution of new Illinois specific market-based solutions to prevent premature closure of nuclear plants."

31. Ibid., 46.

32. Source: Illinois Commerce Commission et al., *Response*, for the supply stack. MISO demand shift is from MISO Energy, *2013 Annual Market Assessment Report: Information Delivery and Market Analysis*, MISO Energy, June 2014, 14, 16, 20.

33. Illinois Commerce Commission et al., *Response*, 46.

34. Ibid., 73.

35. Ibid., 166. "When evaluating the solutions included in this report and any alternatives offered by stakeholders, holistic solutions aimed at solving fundamental market challenges are preferable. The right energy policy has the potential to minimize rate increases to families and businesses while positioning Illinois as a national leader in the development of clean energy. As neighboring states address Clean Power Plan compliance, new clean energy investments by Illinois may offer first-mover advantages in increasingly carbon-constrained energy markets. If Illinois is to move forward with a robust response, the full impact and potential of any such policy must be fully explored."

36. Rowe, *Energy Policy*; Rowe, *Fixing the Carbon Problem*.

37. Sanzillo and Kunkel, *First Energy*.

38. Ibid., 2.

39. Ibid.

40. Illinois Commerce Commission, *Response*, 125.

41. NRC, *2013 Generic Environmental Impact Statement for License Renewal of Nuclear Plants (NUREG-1437)* (Washington, DC: Nuclear Regulatory Commission, 2013).

42. NRC, *2013 GEIS*, 1-30–1-31.

43. NRC, *2013 GEIS*.

44. NRC, *1996 Generic Environmental Impact Statement for License Renewal of Nuclear Plants (NUREG-1437)* (Washington, DC: Nuclear Regulatory Commission, 1996), 8-1.

45. NRC, *2013 GEIS*, Section 2 is entitled "The Alternatives including the Proposed Action." The first 16 pages define the criteria by which the alternatives will be evaluated. The final ten pages present a tabular summary of the findings and the bibliography. The middle 17 pages evaluate all the alternatives considered.

46. NRC, *2013 GEIS*, 1-3. Most utilities are expected to begin preparation for license renewal about 10 to 20 years before expiration of their current operating licenses. Inspection, surveillance, test, and maintenance programs to support continued plant operations during the license renewal term would be integrated gradually over a period of years. Any refurbishment-type activities undertaken for the purposes of license renewal have generally been completed during normal plant refueling or maintenance outages before the original license expires.

47. PG&E, 2015, 7.2-7–7.2-14. This section identifies *standalone* alternatives that PG&E deemed unreasonable, and the bases for these determinations. PG&E accounted for the fact that DCPP provides baseload generation and that any feasible alternative to DCPP would also need to be able to provide baseload power. In performing this evaluation, PG&E relied heavily upon NRC's GElS, 7-2.7. *There may be insufficient operational flexibilities to both meet those renewable power requirements and replace DCPP baseload capacity with wind, solar, and geothermal generation*. Because the power output can only be intermittently generated during the day or during certain seasons, depending on the location, wind turbines are unsuitable for baseload applications. *Wind generation* – therefore, wind generation cannot be considered an adequate replacement of DCPP generation *absent sufficient energy storage to overcome wind's intermittency. Besides pumped-storage hydroelectricity, Compressed Air Energy Storage (CAES) is the technology most suited for storage of large amounts of energy; however, no combination of wind and CAES has yet been proposed at the scale necessary to replace DCPP generation. (7-2.8)* Because solar thermal power is not available 24 hours per day, it is typically not acceptable for baseload applications *absent sufficient energy storage to overcome solar's intermittency…. As noted above, besides pumped-storage hydroelectricity, CAES is the technology most suited for storage of large amounts of energy; however, no combination of CSP and CAES has yet been proposed at the scale necessary to replace DCPP generation.*

7-2.9, While development of battery storage options is ongoing, none are currently available in quantities or capacities that would provide baseload amounts of power. In light of the large contribution of solar PV to potential OG in PG&E service area and limitations on its use as baseload capacity, DG cannot serve as a *reasonable alternative to the baseload generation of DCPP. 7-2.11*, Geothermal plants offer base load capacity similar to DCPP, but it is unlikely to be available *within PG&E's service area* on the scale required to replace the capacity of DCPP, 7-2.12.

48. PG&E, *Diablo Canyon Environmental Report*, PG&E, 2015, 7.2-12.

49. PG&E, *Diablo Canyon Amended Environmental Report*, PG&E, 2014, 7.2-6, 7.2-11, 7.2-12.

50. PG&E, *Diablo Canyon Environmental Report*, 7.2-1.

51. PG&E, *Diablo Canyon Environmental Report*, 7.2-2. Finally, overlaying these concerns about the alternative generation technologies are federal and state greenhouse gas emissions reduction goals. According to EPRI, even while adding renewable capacity equal to 4 times today's wind and solar capacity in 2008, the United States would need to maintain all of its current nuclear capacity, and add 45 more nuclear facilities, to meet greenhouse gas emissions reduction goals.

52. Cooper, *Power Shift*.

53. Tim Judson, "Too Big to Bail Out: The Economic Costs of a National Nuclear Power Subsidy," *Nirsnet*, November 2016.

CHAPTER 9

1. Adam B. Jaffe, Richard G. Newell, and Robert N. Stavins, "A Tale of Two Market Failures: Technology and Environmental Policy," *Ecological Economics* 54 (2005): 164–174.

2. Massimiliano Corradini et al., "Unveiling the Dynamic Relation Between R&D and Emission Abatement: National and Sectoral Innovation Perspectives from the EU," *Ecological Economics* 102 (2014): 48. "Conventional benefit–cost analysis incorporates the normally reasonable assumption that the policy or project under examination is marginal. Among the assumptions this entails is that the policy or project is small, so the underlying growth rate of the economy does not change. However, this assumption may be inappropriate in some important circumstances, including in climate-change and energy policy." Simon Dietz and Cameron Hepburn, "Benefit–Cost Analysis of Non-Marginal Climate and Energy Projects," *Energy Economics* 40 (2013) 61. "We conclude that if there is cause to suspect a project under evaluation is not 'small', in the sense that the range of net benefits might be a significant share of aggregate consumption, then the NPV rule will not suffice. Instead, analysts must fall back on a model, which is capable of evaluating the underlying change in social welfare brought about by the project."

3. W. J. Botzen Wouter and Jeroen C. J. M. van den Bergh, "Specifications of Social Welfare in Economic Studies of Climate Policy: Overview of Criteria and Related Policy Insights," *Environmental and Resource Economics* 58 (2014), 1. This paper shows that applying distinct decision or social welfare criteria can result in different optimal policies of climate control, notably if climate change impacts are uncertain.

Chang Hwang, Frédéric Reynès, and Richard S. Tol, "Climate Policy under Fat-Tailed Risk: An Application of Dice," *Environmental and Resource Economics* 56 (2013), 415. "Uncertainty plays a significant role in evaluating climate policy, and fat-tailed uncertainty may dominate policy advice. Should we make our utmost effort to prevent the arbitrarily large impacts of climate change under deep uncertainty? In order to answer this question, we propose a new way of investigating the impact of (fat-tailed) uncertainty on optimal climate policy: the curvature of the optimal carbon tax against the uncertainty. We find that the optimal carbon tax increases as the uncertainty about climate sensitivity increases, but it does not accelerate as implied by Weitzman's Dismal Theorem. We find the same result in a wide variety of sensitivity analyses. These results emphasize the importance of balancing the costs of climate change against its benefits, also under deep uncertainty."

4. Marc D. Davidson, "Zero Discounting Can Compensate Future Generations for Climate Damage," *Ecological Economics* 105 (2014), 40. "Most people share the moral intuition that we ought to refrain from harming others, and ought to compensate them if we were unable to prevent harm. To regain a reflective equilibrium between such deontological intuitions and economic theory there is a need to accept different discount rates for different situations: a zero consumption discount rate in the case of cost–benefit analysis of measures to prevent wrongful harm to future generations, and standard discounting in all other cases. Applying a zero consumption discount rate means that future generations are automatically largely compensated for climate damage that remains unmitigated."

John E. Roemer, "Once More on Intergenerational Discounting in Climate-Change Analysis: Reply to Partha Dasgupta," *Environmental and Resource Economics* 56 (2013), 141, that every individual, no matter when born, has an equal right to well-being. That justification is that future generations may not exist. In an earlier article published here, I explained this view, and criticized economists who deviate from it: the practical aspect of this deviation is to choose discount rates which are far too high, thus relegating future generations to lower utility than they a priori have a right to.

5. Jonathan Aldred, "Justifying Precautionary Policies: Incommensurability and Uncertainty," *Ecological Economics* 96 (2013), 132. "When decisions are taken in conditions of Keynesian or Knightian uncertainty, and when there is a threat of serious or irreversible environmental damage, the Precautionary Principle is often recommended to guide decision making. However, the Precautionary Principle has been widely criticized. In response to these criticisms, a qualitative version of the Precautionary Principle is developed which draws its normative content from a blend of formal decision theory and political philosophy. It is argued that precautionary action can be justified by some flexible combination of uncertainty and incommensurability. The 'greater' the uncertainty, the 'less' incommensurability is required to justify precautionary action, and vice versa. Throughout the paper, the arguments are explored using the example of climate change decision problems."

6. Oskar Lecuyer and Phillippe Quirion, "Can Uncertainty Justify Overlapping Policy Instruments to Mitigate Emissions?" *Ecological Economics* 93 (2013): 177–191.

7. Qui and Anadon, "The Price of Wind"; Emanuele Massetti and Lea Nicita, *The Optimal Climate Policy Portfolio*, CESifo Working Paper no. 2988, Energy and Climate Economics, 2010.

8. Dechezlepetre et al., *Climate Change & Directed Innovation*.

9. Mitigation is the master strategy, but as significant impacts appear to be unavoidable, adaptation is recognized as a strong complementary strategy both to alleviate harms and to capture synergies that can lower total costs. Klein, et al., "Adaptation and Mitigation"; M. L. Parry et al., *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, U.K. and New York, NY: Cambridge University Press, 2007); Illman et al., *Scoping Study*; and Landauer, Juhola, and Söderholm, "Adaptation and Mitigation."

10. Grubb, Chapuis, and Duong, "Economics of Changing Course"; Popp, Newell, and Jaffe, "Energy, the Environment, and Technological Change"; Dechezleperte et al., *Climate Change & Directed Innovation*; Johnstone and Hascic, *Directing Technological Change*; Luderer, "Economic Mitigation Challenges."

11. Gerlagh, "Induced Technological Change"; Gerlagh, Kverndokk, and Rosendhal, "Optimal Timing"; Kalkuhl, Edenhofer, and Lessmann, "Learning or Lock-in"; Acemoglu et al., "Dedicated Technical Change; Gross et al., *On Picking Winners*; Nordhaus, "Friendly Space for Technological Change." This observation has crossed over to the popular press: Leonhardt, "There's Still Hope"; Avent, "Creating the Clean Economy."

12. Bosetti and De Cian, "A Good Opening"; Ek and Soderholm, "Technology Learning"; Kahouli Brahmi, "Technological Learning," 36; Kalkuhl, Edenhofer, and Lessmann, "Learning or Lock-in"; Lindman and Soderholm, "Wind Power Learning Rates"; Rubin, "Learning Rates for Electricity Supply"; and Lindahl, Bodin, and Tengö, "Governing Complex Commons."

13. Nordhaus, Shellenberger, and Trembath, "Carbon Taxes and Energy Subsidies," calculate that that targeted subsidies yield approximately three times the incentive to invest in low carbon alternatives (compared to coal) as a general carbon tax. There is also the problem of the creation of large rents that do not contribute to efficiency. Holmes and Mohanty, *Macroeconomic Benefits*, 12. "This is because carbon prices rise considerably to drive additional investment in the absence of technology-support mechanisms. This pushes up the cost of gas generation and the overall costs. Since gas generation sets the wholesale prices on the marginal plants this would result in higher rents to existing low carbon generators and higher government revenues from the carbon floor price mechanism."

14. Grubb, Chapuis, and Duong, "Economics of Changing Course, 428.

15. In one recent example, Jihoon Min et al., "Labeling Energy Cost on Light Bulbs Lowers Implicit Discount Rates," *Ecological Economics* 97 (2014), finds an implicit discount rate for light bulbs of 100 percent.

16. See e.g., Katherine D. Arbuthnott and Brett Dolter, "Escalation of Commitment to Fossil Fuels," *Ecological Economics* 89 (2013), 7; Qui, Colson, and Grebitus, Risk Preferences and Purchase of Energy-Efficient Technologies in the Residential Sector," *Ecological Economics* 107 (2014), 216.

17. See e.g., Shuling Chen Lillemo, "Measuring the Effect of Procrastination and Environmental Awareness on Households' Energy-Saving Behaviours: An Empirical Approach," *Energy Policy* 66 (2014).

18. See e.g., Koichiro Ito, "Do Consumers Respond to Marginal or Average Price? Evidence from Nonlinear Electricity Pricing," *The American Economic Review* 104 (2014), 537.

19. See e.g., Jonn Axsen, Caroline Orlebar, and Stephen Skippon, "Social Influence and Consumer Preference Formation for Pro-Environmental Technology: The Case of a U.K. Workplace Electric-Vehicle Study," *Ecological Economics* 95 (2013), 96.

20. While the sensitivity to a range of socioeconomic factors is to be expected, other variation is surprising: e.g., Heidi Bruderer Enzler, Andreas Diekmann, and Roto Meyer, "Subjective Discount Rates in the General Population and Their Predictive Power for Energy Saving Behavior," *Energy Policy* 65 (2014); Henrik Andersson et al., "Willingness to Pay and Sensitivity to Time Framing: A Theoretical Analysis and an Application on Car Safety," *Environmental and Resource Economics* 56 (2013), 437.

21. See e.g., Kenneth S. Kurani and Thomas S. Turrentine, *Automobile Buyer Decisions about Fuel Economy and Fuel Efficiency: Final Report to United States Department of Energy and Energy Foundation*, Institute of Transportation Studies University of California, September 2004, 1.

22. See e.g., Lucas W. Davis, *Evaluating the Slow Adoption of Energy Efficient Investments: Are Renters Less Likely to Have Energy Efficiency Appliances?* Energy Institute at Haas, June 2010, 1; Loren Lutzenheiser et al., *Market Structure and Energy Efficiency: The*

Case of New Commercial Buildings, California Institute for Energy Efficiency, 2001, cited in Blumstein and Taylor, *Rethinking the Energy-Efficiency Gap*, viii.

23. Gabaix Xaviar and David Laibson, *Shrouded Attributes, Consumer Myopia, and Information Suppression in Competitive Markets*, NBER Working Paper 11755, November 2005; Tanjim Hosain and John Morgan, *Shrouded Attributes and Information Suppression: Evidence from Field Experiments* (Competition Policy Center, UC Berkeley, September, 2006); Jennifer Brown, Tanjim Hossain, and John Morgan, *Shrouded Attributes and Information Suppression: Evidence from the Field* (Working Paper, Haas Institute at Berkeley, November 2007); Stefano DellaVigna, "Psychology and Economics: Evidence from the Field," *Journal of Economic Literature* 47 (2009): 315–372; Glenn Ellison and Sara Ellison, "Search, Obfuscation, and Price Elasticities on the Internet," *Econometrica* 77 (2009): 427–452; Paul Heidhues and Botond Kőszegi, "Naivete-Based Discrimination," Working Paper, 2015; Sumit Agarwal, Changcheng Song, and Vincent Yao, *Banking Competition and Shrouded Attributes: Evidence from the US Mortgage Market*, July 2016.

24. See e.g., Emiko Inoue, Toshi H. Arimura, and Makiko Nakano, "A New Insight into Environmental Innovation: Does the Maturity of Environmental Management Systems Matter?" *Ecological Economics* 94 (2013), 162; our finding shows that the organizational and managerial factors of firms are important in examining environmental R&D.

25. See e.g., Carlos Montalvo, "General Wisdom Concerning the Factors Affecting the Adoption of Cleaner Technologies: A Survey 1990–2007," *Journal of Cleaner Production* 16 (2008), S11.

26. See e.g., Sorrel, Mallet, and Nye, *Barriers to Industrial Energy Efficiency*, iii.

27. Sardianou, "Barriers to Industrial Energy Efficiency Investment in Greece," *Journal of Cleaner Production* 16 (2008), 1417.

28. See e.g., Montalvo, "General Wisdom," S10.

29. See e.g., Horbach, "Determinants of Environmental Innovations," 172.

30. See e.g., Enrica de Cian and Tavoni Massimo, "Mitigation Portfolio and Policy Instruments When Hedging against Climate Policy and Technological Uncertainty," *Environmental Model Assessment* 17 (2012), 123; Tooraj Jamasb and Jonathan Kohler, *Learning Curves for Energy Technology: A Critical Assessment*, Cambridge Working Paper 0752, University of Cambridge, October 2007, 8.

31. See e.g., Sorrel, Mallet, and Nye, *Barriers to Industrial Energy Efficiency*, 67; Sardianou, "Energy Efficiency Investment in Greece," 1402.

32. See e.g., Sabine Fuss and Jana Szolgayosva, "Fuel Price and Technological Uncertainty in a Real Option Model for Electricity Planning," *Applied Energy* 87 (2010), 2938.

33. Wilkinson, *Behaviorial Economics*, Table 5.1.

34. See e.g., Enzler, Diekmann, and Meyer, "Subjective Discount Rates," 524; Jihoon Min et al., "Energy Cost on Light Bulbs"; Michael Li et al., "Are Residential Customers Price-Responsive to an Inclining Block Rate? Evidence from British Columbia, Canada," *The Electricity Journal* 27 (2014); Huecker, "Community and Virtual Net Metering: Overcoming Barriers to Distributed Generation," *gwujeel.files.wordpress.com*, 2013.

35. Roemer, "Once More"; Davidson, "Zero Discounting"; Jennifer Jacquet et al., "Intra- and Intergenerational Discounting in the Climate Game," *Nature Climate Change* 3 (2013); Therese C. Grijalva, Jayson L. Lusk, and W. Douglass Shaw, "Discounting the Distant Future: An Experimental Investigation," *Environmental and Resource Economics* 59 (2014).

36. See e.g., Davidson, "Zero Discounting"; Roemer, "Once More," 141; Jacquet et al., "Intra- and Intergenerational Discounting"; Grijalva, Lusk, and Shaw, "Discounting the Distant Future."

37. Robert Gross, William Blyth, and Philip Heponstall, "Risks, Revenues and Investment in Electricity Generation: Why Policy Needs to Look Beyond Costs," *Energy Economics* 32 (2010), 798, offer a similar observation with the broader question of the use of levelized cost analysis, pointing out that "levelised costs may be useful (despite cost uncertainties) in deciding *whether* support is needed, but are not sufficient alone to determine *how* to provide it."

38. Biewald, *Economics of Electric Sector CO_2 Emissions Reduction: Making Climate Change Policy that People Can Live With*, NASUCA 2008 Annual Meeting, November 18, 2008, 5.

39. Gross et al., *On Picking Winners*.

40. Ibid., 11. Ian Temperton, "Dining Out on Electricity Market Reform with Kylie, the Tooth Fairy and a Spherical Horse in a Vacuum," *Climate Change Capital*, 2012.

41. Gross et al., *On Picking Winners*, 12.

42. Avent, "Creating the Clean Economy."

43. Ibid.

44. Leonhardt, "There's Still Hope."

45. Richard B. Howarth and Alan H. Sanstad, "Discount Rates and Energy Efficiency," *Contemporary Economic Policy*, 13 (2007), 108.

46. Richard B. Howarth and Bo Anderson, "Market Barriers to Energy Efficiency," *Energy Economics*, 15 (1993), 264, 270.

47. De la Rue du Can et al., "Design of Incentive Programs."

48. Burtraw and Woerman, "Economic Ideas."

49. Ibid.

50. Gross et al., *On Picking Winners*, 18.

51. Marcelo Bianconi and Joe A. Yoshino, "Risk Factors and Value at Risk in Publicly Traded Companies of the Nonrenewable Energy Sector," *Energy Economics* 45 (2014), refer to this as the escalation of commitment. See also Bloomberg New Energy Finance, *Fossil Fuel Divestment: A $5 Trillion Challenge*, White Paper, August 2014; Arbuthnott and Dolter, "Escalation of Commitment"; Farrar-Rivas and Ferguson, *Emerging Research on Climate Change Risk and Fossil-Fuel Divestment*, Veris, July 2014; CERES, "Investors Challenge Fossil Fuel Companies," *CERES*, 2013.

52. Acemoglu et al., "Dedicated Technical Change," 132.

53. Gross et al., *On Picking Winners*.

54. Ibid.; Massetti and Nicita, *Optimal Climate Policy*, 1.

55. Qui and Anadon, "The Price of Wind"; Massetti and Nicita, *Optimal Climate Policy*.

56. Dechezlepetre et al., *Climate Change & Directed Innovation*.

57. Grubb, Chapuis, and Duong, "Economics of Changing Course," 428.

58. Zelenika-Zovko and Pearce, "Diverting Indirect Subsidies from the Nuclear Industry to the Photovoltaic Industry: Energy and Financial Returns," *Energy Policy* 39 (2011).

59. Enrica De Cian, Samuel Carrara, and Massimo Tavoni, *Innovation Benefits from Nuclear Phase-Out: Can They Compensate the Cost?* Fondazione Eni Enrico Mattei, 2012, 14.

60. Enrica De Cian, Samuel Carrara, and Massimo Tavoni, "Nuclear Expansion or Phase Out? Costs and Opportunities," *Review of Environment, Energy and Economics*, January 9 2014, doi:10.7711/feemre3.2014.01.001, 1–2.

61. Pfund and Healy, *What Would Jefferson Do?*

62. Goldberg, *Federal Energy Subsidies*; Matthew Slavin, "The Federal Energy Subsidy Scorecard: How Renewables Stack Up," *Renewable Energy World.com*, November 3, 2009; Kadra Branker, Michael Pathak, and Joshua M. Pearce, "A Review of Solar Photovoltaic

Levelized Cost of Electricity," *Renewable and Sustainable Energy Reviews* 15 (2011): 4470–4482; Jeremy Badcock and Manfred Lenzen, "Subsidies for Electricity-Generating Technologies: A Review," *Energy Policy* 38 (2010); Pfund and Healy, *What Would Jefferson Do?*

63. BWE, German Wind Energy Association, *The Full Costs of Power Generation: A Comparison of Subsidies and Societal Cost of Renewable and Conventional Energy Sources*, BWE, Berlin, August 2012; Lucy Kitson, Peter Wooders, and Tom Moerenhout, *Subsidies and External Costs in Electric Power Generation: A Comparative Review of Estimates* (Geneva, Switzerland: International Institute for Sustainable Development, 2011); Ann G. Berwick, *Comparing Federal Subsidies for Renewables and Other Sources of Electric Generation*, Massachusetts Department of Public Utilities Massachusetts Solar Summit, June 13, 2012; U.S. Energy Information Administration, *Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2010* (Washington, DC: U.S. Government Printing Office, 2011); Pfund and Healey, *What Would Jefferson Do?*; U.S. GAO, *Federal Electricity Subsidies: Information on Research Funding, Tax Expenditures, and Other Activities That Support Electricity Production*, GAO-08-102 (Washington, DC: U.S. Government Printing Office, 2007); Goldberg, *Federal Energy Subsidies*.

64. Bettencourt, Trancik, and Kaur, "Global Innovation in Energy."

65. Badcock and Lenzen, "Subsides for Electricity-Generating"; Branker, Pathak, and Pearce, "A Review of Solar Photovoltaic."

66. See e.g., de Cian and Massimo, "Mitigation Portfolio," 133. "Against this evidence, regulation such as Emissions Performance Standards (EPS) that set a maximum threshold for the emission intensity of power generation in terms of grams of CO_2 per kilowatt hour could be justified as a way to reduce uncertainty exposure. . . . We have also pointed out that the optimal penetration of renewables is slow, even when facing a given deterministic carbon price." Cooper, *All Risk, No Reward*, 64.

67. Kirsten Gram-Hanssen, "Efficient Technologies or User Behaviour, Which Is the More Important When Reducing Households' Energy Consumption?" *Energy Efficiency* 6 (2013), 447. Through the presentation of these different projects and examples, it is shown how user behavior is at least as important as the efficiency of technology when explaining households' energy consumption in Denmark. In relation to energy policy, it is argued that it is not a question of technology efficiency or behavior, as both have to be included in future policy if energy demand is actually to be reduced. Furthermore, it is also argued that not only individual behavior is relevant, but also a broader perspective on collectively shared low carbon practices has to be promoted. Hossein Estiri, "Building and Household X-Factors and Energy Consumption at the Residential Sector: A Structural Equation Analysis of the Effects of Household and Building Characteristics on the Annual Energy Consumption of US Residential Buildings," *Energy Economics* 43 (2014), 178; Results demonstrate that the direct impact of household characteristics on residential energy consumption is significantly smaller than the corresponding impact from the buildings. However, accounting for the indirect impact of household characteristics on energy consumption, through choice of the housing unit characteristics, the total impact of households on energy consumption is just slightly smaller than that of buildings. Outcomes of this paper call for smart policies to incorporate housing choice processes in managing residential energy consumption.

68. Louis-Gaëtan Giraudet and Sébastien Houde, *Double Moral Hazard and the Energy Efficiency Gap*, E2e Working Paper 009, August 2014, 1. Moral hazard problems are consistent with homeowners investing with implied discount rates in the 15-35% range. Finally, we find that minimum quality standards outperform energy-savings insurance. Olivia Guerra-Santin, and Laure Itard, "The Effect of Energy Performance Regulations on Energy Consumption," *Energy Efficiency* 5 (2012), 269; "The results showed that energy reductions

are seen in dwellings built after the introduction of energy performance regulations. However, results suggest that to effectively reduce energy consumption, the tightening of the EPC is not enough. Policies aimed at controlling the construction quality and changing occupant behavior are also necessary to achieve further energy reductions." Peter S. Mallaburn and Nick Eyre, "Lessons from Energy Efficiency Policy and Programmes in the UK from 1973 to 2013," *Energy Efficiency* 7 (2014), 36. Most rapid improvements in energy efficiency result from programmes with a carefully managed combination of government intervention (which is generally regulation-led) and market support. Energy efficiency requires capital investment, and lack of up-front capital is an important barrier in all sectors. However, unlike other policies, energy efficiency policy does create a return on the investment, which, with creative policy design, can be used to offset the cost. Some policies are very effective in doing this. Technology standards and labelling schemes are good examples, such as EU energy labelling and minimum performance standards for domestic goods and the government's Energy Technology List for industrial process equipment eligible for accelerated capital allowances. The evidence is that, with good policy design, end-user costs are negative as long as the energy saving benefits exceed the costs and the market is given time to adjust. The early energy efficiency programmes focused on technologies. But developments in social and behavioral science show that policies need to address the demand-side as well: energy efficiency is about people as well as products.

69. Martin Junginger et al., *Technological Learning in the Energy Sector,* Universities Utrach and Energy Research Centre of the Netherlands, April 2008, 12; Takahiko Kiso, *Environmental Policy and Induced Innovation: Evidence from Automobile Fuel Economy Regulation*. Working Paper, 2009, finds for Japanese automobiles that "fuel economy improvement accelerated after regulations were introduced, implying induced innovation in fuel economy technology."

70. Larry Dale et al., "Retrospective Evaluation of Appliance Price Trends," *Energy Policy* 37 (2009).

71. Dan Sperling et al., *Analysis of Auto Industry and Consumer Responses to Regulation and Technological Change and Customization of Consumer Response Models in Support of AB 1493 Rulemaking,* Institute of Transportation Studies, UC Davis, June 1, 2004, 10–15.

72. Onno Kuok, *Environmental Innovation Dynamics in the Automotive Industry: A Case Study in the Framework of the Project "Assessing Innovation Dynamics Induced by Environmental Policy*," E-07-01, Institute for Environmental Studies, November 3, 2006; "The European car industry is highly dynamic and innovative. Its R&D expenditures are well above average in Europe's manufacturing sector. Among the most important drivers of innovation are consumer demand (for comfort, safety, and fuel economy), international competition, and environmental objectives and regulations. . . . One element of success of technology forcing is to build on one or more existing technologies that have not yet been proven (commercially) in the area of application. For improvements in the fuel economy of cars, many technological options are potentially available. . . . With respect to innovation, the EU and Japanese policy instruments perform better than the US CAFE [Corporate Average Fuel Economy] program. This is not surprising, given the large gap between the stringency of fuel-efficiency standards in Europe and Japan on the one hand and the US on the other. . . . One of the reasons for the persistence of this difference is that the US is not a significant exporter of cars to the European and Japanese markets."

73. Nadel and DeLaski, *Appliance Standards*.

74. Cooper, *Energy Efficiency Performance Standards*.

75. Burtraw and Woerman, "Economic Ideas," 525.

76. Cameron Hepburn, "Environmental Policy, Government, and the Market," *Oxford Review of Economic Policy* 26 (2010).

77. Ibid., 122.
78. Ibid., 127.
79. Ibid., 119.
80. Ibid., 117.
81. Ibid., 117.
82. Ibid., 120, "growth faltered in the 1970s with the two oil shocks and the collapse of the Bretton Woods system. These conditions ushered Margaret Thatcher into power in the UK in 1969, and Ronald Reagan in the US in 1970, with a corresponding change in political philosophy."
83. Ibid., 125, "The last decade, the left-leaning government in the UK has enlarged the state, and has further extended its reach following the global financial crisis which served as a reminder that asset markets are subject to booms and busts and are not self-regulating. Greenspan, risk in financial markets are regulated by private parties."
84. Ibid., 120.
85. Ibid., 122.
86. Ibid., 117.
87. Stiglitz, "Phony Capitalism," *Harper's Magazine*, September 2014.
88. Stiglitz, "Phony Capitalism"; because inequality is a central source of dynamism and tension in the capitalist mode of production, Piketty's analysis (*Capital in the 21st Century*) has elicited strongly critical reactions from right to left. From the perspective of the theory adopted in this paper, in addition to Stgilitz's critique based on policy, Acemoglu and Robinson ("General Laws of Capitalism") have pointed out the absence of institutional analysis and critical process of endogenous technological change. Nuno Ornelas Martins (*Inequality, Sustainability and Piketty's Capital*, Catholic University of Portugal, Economic Working Papers, No. 5, 2014) notes the marginalist assumptions; Philippe Aghion et al., *Innovation and Top Income Inequality*, NBER Working Paper No. 21247, June 2015, present a confirmation of the Schumpeterian hypothesis on rewards to innovation.
89. Stiglitz, "Phony Capitalism."

CHAPTER 10

1. For example, see Ken Costello, *Making the Most of Alternative Generation Technologies: A Perspective on Fuel Diversity*, NRRI, March 2005; Andrew Stirling, "Multicriteria Diversity Analysis: A Novel Heuristic Framework for Appraising Energy Portfolios," *Energy Policy* 38 (2010): 10.
2. Andrew Mills and Ryan Wiser, *Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California*, Lawrence Berkeley National Laboratory, 2012, 1.
3. Ron Binz et al., *Practicing Risk-Aware Electricity Regulation: What Every State Regulator Needs to Know* (Boston, MA: Ceres, 2012), 1.
4. In addition to Mills and Wiser, *Changes in the Economic Value*, and Ron Binz et al., *Practicing Risk-Aware Electricity Regulation*, recent "how to" proposals include, for example, Scott Hempling, *A Guide for Ontario Energy Policy Makers: Multi-Criteria Design Analysis to Develop Sound Energy Policy & Promote Green Energy*, 2011; Geoff Keith et al., "Toward a Sustainable Future for the U.S. Power Sector: Beyond Business as Usual," *Synapse*, November 16, 2011; Evan Mills, "Weighing the Risks of Climate Change Mitigation Strategies," *Bulletin of the Atomic Scientists* 68 (2012); Office of Ohio Consumers' Council, *Integrate Portfolio Management in a Restructured Supply Market*, 2006; William Steinhurst

et al., *Energy Portfolio Management: Tools & Resources for State Public Utility Commissions*, NARUC 2006; Tennessee Valley Authority, *TVA's Environmental and Energy Future*, 2011.

5. Shimon Awerbuch and Martin Berger, *Applying Portfolio Theory to EU Electricity Planning and Policy-Making,* IEA/EET Working Paper, February 2003, 5.

6. Gene B. Alleman, *Five Easy Pieces of Risk Management*, Colorado Springs, May 8, 2008; Stephen Schrader, William M. Riggs and Robert P. Smith, *Choice over Uncertainty and Ambiguity in Technical Problem Solving,* Alfred Sloan School of Management, Working Paper #3533-93-BPS, 1993; Robert B. Duncan, "Characteristics of Organizational Environments and Perceived Environmental Uncertainty," *Administrative Science Quarterly,* (17) 1972.

7. Andrew Stirling, *On the Economics and Analysis of Diversity,* SPRU Paper No. 28, University of Sussex, 2000, 15–16.

8. Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable* (New York: Random House, 2007), xx–xxi.

9. Clauzwitz is credited with the metaphor, cited in Eugenia C. Kiesling, "On War Without the Fog," *Military Review*, September–October (2001).

10. David A. Maluf, Yui O. Gawdisk, and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety*, NASA Technical Reports, 2005.

11. The problem of complexity of the analytic frameworks as a barrier to adoption has been noted by analyses working within the portfolio framework, e.g., Fabien A. Roques, "Analytic Approaches to Quantify and Value Fuel Mix Diversity," Working Paper, 2008; and J. C. Jansen, L. W. M. Beurskens, and X. van Tilburg, *Application of Portfolio Analysis to the Dutch Generating Mix*, ECN-C-05-100, February 2006.

12. Technology Risk Management Analysis used the word incertitude to describe the overall challenge and ambiguity to describe what we call vagueness. I use the term vagueness as opposed to ambiguity based on the following definitions. Stirling used fuzzy logic as the analytic tool in this sector, and Wikipedia uses fuzzy logic to elaborate on the definition of vagueness.

Ambiguity is a term used in writing and math, and under conditions where information can be understood or interpreted in more than one way and is distinct from vagueness, which is a statement about the lack of precision contained or available in the information. Context may play a role in resolving ambiguity. For example the same piece of information may be ambiguous in one context and unambiguous in another.

The term **vagueness** denotes a property of concepts (especially predicates). A concept is vague if the concept's extension is unclear; if there are objects which one cannot say with certainty whether they belong to a group of objects which are identified with this concept or which exhibit characteristics that have this predicate (so-called "border-line cases"); In everyday speech, vagueness is an inevitable, often even desired effect of language usage. However, in most specialized texts (e.g., legal documents) vagueness is distracting and should be avoided whenever possible.

Fuzzy logic: One theoretical approach is that of fuzzy logic, developed by American mathematician Lotfi Zadeh. Fuzzy logic proposes a gradual transition between "perfect falsity," for example, the statement "Bill Clinton is bald," to "perfect truth," for, say, "Patrick Stewart is bald." In ordinary logics, there are only two truth-values: "true" and "false." The fuzzy perspective differs by introducing *an infinite number of truth-values* along a spectrum between perfect truth and perfect falsity. Perfect truth may be represented by "1," and perfect falsity by "0." Borderline cases are thought of as having a "truth-value" anywhere between 0 and 1 (for example, 0.6).

13. Taleb, *The Black Swan*, 213.

14. Stirling, *On the Economics and Analysis of Diversity*, 15.

15. Ibid.

16. Taleb, *The Black Swan*, xxii.

17. Taleb, "The Fourth Quadrant: A Map of the Limits of Statistics," *Edge*, December 18, 2016, 30.

18. Taleb, *The Black Swan*, 317.

19. Andrew Stirling, *On Science and Precaution in the Management of Technological Risk*, European Science and Technology Observatory, 2001, 16.

20. Ibid., 56.

21. Ibid., 15–17.

22. Taleb, *The Black Swan*, xx–xxi.

23. Ibid., 364–365.

24. Ibid.

25. Ibid.

26. Taleb, "The Fourth Quadrant," 16.

27. Arnoud de Meyer, Christoph H. Loch, and Michel Pich, "Managing Project Uncertainty: From Variation to Chaos," *MIT Sloan Management Review*, Winter (2002), 67.

28. Gene B. Alleman, *Five Easy Pieces of Risk Management*, May 8, 2008.

29. Schrader, Stephen, William M. Riggs, and Robert P. Smith, *Choice over Uncertainty and Ambiguity in Technical Problem Solving,* Alfred Sloan School of Management, Working Paper #3533-93-BPS, February 1993.

30. de Meyer, Loch, and Pich, "Managing Project Uncertainty," 67.

31. Clauzewitz is credited with the metaphor based on quotes like, "War is the realm of uncertainty; three quarters of the factors on which action is based are wrapped in a fog of greater or lesser uncertainty." "The great uncertainty of all data in war is a peculiar difficulty, because all action must, to a certain extent, be planned in a mere twilight, which in addition not infrequently—like the effect of a fog or moonshine—gives to things exaggerated dimensions and unnatural appearance" (cited in Kiesling, "On War Without the Fog").

32. Kiesling, "On War Without the Fog."

33. Alan D. Campden, "Cyberspace Spawns a New Fog of War," *SIGNAL Magazine*, September 2010, xx.

34. Eric Bland, "Fog of War Demystified by Financial 'Power Law,'" *Discovery News*, January 7, 2010, xxx.

35. Maluf, Gawdisk, and Bell, *On Space Exploration and Human Error*.

36. Grubb, Chapuis, and Duong, "The Economics of Changing Course"; Awerbuch and Berger, *Applying Portfolio Theory*; Shimon Awerbuch, *Portfolio-Based Electricity Generation Planning*, REEEP, Environment Policy Department, Foreign and Commonwealth Office, London, May 2004; Eoin McLoghlin and Morgan Bazilian, *Application of Portfolio Analysis to the Irish Generating Mix in 2020,* Sustainable Energy Ireland, June 2006; Christopher Möller, Svetlozar T. Rachev, and Frank J. Fabozzi, "Balancing Energy Strategies in Electric Portfolio Management," *Energy Economics* 33 (2011); Erik Delarue et al., "Applying Portfolio Theory to the Electricity Sector: Energy versus Power," *Energy Economics* 33 (2011): 12–23.

37. In single price auction markets, where inframarginal suppliers receive the market clearing price, the impact on consumers is magnified by the collection of substantial rents. For the United Kingdom, see E3G. In the United States the issue has received attention as part of the debate over the "supply-induced price effects" (Fagan et al., *Potential Rate Effects*, 34) of the production tax credit for wind.

38. The original ideas were presented in a series of papers by L. A. Zadeh ["Fuzzy sets," *Information and Control* 8 (1965); "Fuzzy logic," *IEEE Computer* 21 (1968)] in the 1960s.

The first logic controller was built at the University of London in 1973. David Dery, "Fuzzy Control," *Journal of Public Administration Research and Theory* 12 (2002); Jason H. T. Bates and Michael P. Young, "Applying Fuzzy Logic to Medical Decision Making in the Intensive Care Unit," *American Journal of Respiratory and Critical Care Medicine* 167 (2003); Goyol Madhu, Jie Lu, and Guang Zang, "Decision Making in Multi-Issue E-market Auctioning Using Fuzzy Techniques and Negotiable Attitudes," *Journal of Theoretical and Applied Electronic Commerce Research* 3 (2008): 97–110; and Jose L. Salmeron, "Supporting Decision Makers with Fuzzy Cognitive Maps," *Research Technology Management*, 52 (2009), suggest the application to human decision making.

39. Several of the analyses of technology costs recognize this, using different costs of capital for different technologies and assuming that the cost of capital declines over time as technologies mature.

40. Dhiman Chatterjee and V. C. Ramseh, "Real Options for Risk Management in Information Technology Projects," in *Proceedings of the 32nd Hawaii International Conference on System Sciences* (Washington, DC: IEEE, 1999); Jaroslava Hlouskova et al., *Real Option Models and Electricity Portfolio Management*, Discussion Paper No. 9, OSCOGEN, May 2002; Pauli Murto and Gjermund Nese, *Input Price Risk and Optimal Timing of Energy Investment: Choice Between Fossil and Biofuels*, System Analysis Laboratory, Helsinki University of Technology, 2002; Michael Siclari and Giuseppe Castellacci, *Real Options for Flexible Power Generation Modeling*, Energy Risk International, 2004; William Blyth et al., "Investment Risk under Uncertain Climate Change Policy," *Energy Policy* 35 (2007); Mohamad Ben Abdelhamid, Chakar Aloui, and Corinne Chaton, "A Real Options Approach to Investing in the First Nuclear Power Plant Under Cost Uncertainty: Comparison with Natural Gas Power Plant for the Tunisian Case," *International Journal of Oil, Gas and Coal Technology* 2 (2009).

41. Doug Gardner and Yiping Zhuang, "Valuation of Power Generation Assets: A Real Options Approach," *ALGO Research Quarterly* 3 (2000), 9.

42. Blyth et al., "Investment Risk," 5268.

43. Andrew Stirling, "Diversity and Ignorance in Electricity Supply Investment: Addressing the Solution Rather Than the Problem," *Energy Policy* 22 (1994); Stirling, *Economics and Analysis of Diversity*; Andrew Stirling, "Risk, Precaution and Science: Towards a More Constructive Policy Debate," *EMBO Reports* 8 (2007); Stirling, Andrew, "A General Framework for Analyzing Diversity in Science, Technology and Society," *Interface, Journal of the Royal Society* 4 (2007); Michael Grubb, Lucy Butler, and Paul Twomey, "Diversity and Security in UK Electricity Generation: The Influence of Low-Carbon Objectives," *Energy Policy* 34 (2006); Go Yoshizawa, Andy Stirling, and Tatsujiro Suzuki, *Electricity System Diversity in the UK and Japan - A Multi-criteria Diversity Analysis*, University of Sussex, SEWPS, Paper No. 176, 2009; Stirling, "Multicriteria Diversity Analysis."

CHAPTER 11

1. Awerbuch and Berger, *Applying Portfolio Theory*.
2. Ibid.
3. Taleb, "The Fourth Quadrant," 3.
4. R. Walz, J. Schleich, and M. Ragwitz, *Regulation, Innovation and Wind Power Technologies: An Empirical Analysis for OECD Countries*, DIME Final Conference, Maastricht, April 2011, 5; By and large, these case studies assess especially feed-in-tariffs as favorable. The specific advantage of feed-in-tariffs is seen in lower transaction costs and reduced risk perception for investors and innovators, which are extremely important especially for new

entrants and financial institutions. Gross, Blyth, and Heponstall, "Risks, Revenues and Investment," 803. "The second main conclusion is that policymakers can choose whether to reduce, or remove price risks through the design of incentive scheme. Doing so can make policies more effective in terms of delivering investment. . . . The arguments provided in this paper lend support to the notion that the government is right to be considering fixed price support in markets where investors are risk averse . . . or where technological undertainties are large." Kalkuhl, Edenhoffer, and Lessman, "Learning or Lock-In," 1. "To guide government intervention, we compare welfare-maximizing technology policies including subsidies, quotas, and taxes with regard to their efficiency, effectivity, and robustness. Technology quotas and feed-in-tariffs turn out to be only slightly less efficient than first-best subsidies and seem to be more robust against small purturbances."

5. Gerlagh, Kverndokk, and Rosendahl, "Optimal Timing of Climate Change Policy," 388. "If the public authority can directly steer the development of energy-related technology, either through public energy-related R&D or through targeted private R&D, then it is efficient to spend much of the initial effort on this technological development. . . . However, if the public authority cannot directly determine the development of an emission reducing technology, then efficiency considerations suggest that the clean technology should be extra stimulated through an increased demand for its produced goods. The technology pull policy should be relatively strong during the emerging phase of climate change problems, when the abatement technologies still have to mature."

6. Johnstone and Hascic, *Directing Technological Change*, 8. List six such strategies, improved weather forecasting, geographic dispersal of intermittent renewable energy plants, diversity in the portfolio of reneeable energy resources, trade in electricity supply services, improvements in load management, and energy storage.

7. Ibid., 25. "Since innovating in storage technologies is an important complement to innovation in all intermittent renewable generating technologies such a strategy reduces the risk of (not) picking winners. Moreover, the technologies are at a relatively early stage of development, with greater need for support."

8. Costello, *Perspective on Fuel Diversity*.

9. Jansen, Beurskens, and van Tilburg, *Application of Portfolio Analysis*, 13, argue for a risk-cost frontier.

10. Ibid., Appendix, 59, "the question of whether a tool could be developed for gauging the impact of incremental technology deployment . . . the use of a (sort of) Sharpe ratio, showing the tangent of the direction a certain portfolio at (or to the right of) the efficient frontier would move into by incremental use of a certain technology."

11. Ibid.

12. Paul Watkiss et al., "The Use of New Economic Decision Support Tools for Adaptation Assessment: A Review of Methods and Applications, Towards Guidance on Applicability," *Climatic Change* 132 (2015), 401–416.

13. Rauch, "Price and Risk Reduction Opportunities."

14. Shimon Awerbuch and Spencer Yang, "Using Portfolio Theory to Value Power Generation Investments," in *Analytic Methods for Energy Diversity and Security*, ed. Morgan Bazilian and Fabien Rocques (Oxford, U.K.: Elsevier, 2008).

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1. http://www.nbcnews.com/politics/2016-election/donald-trump-pledges-rip-paris-climate-agreement-energy-speech-n581236.

2. Mark Cooper, "Renewable and Distributed Resources in a Post-Paris Low Carbon Future: The Key Role and Political Economy of Sustainable Electricity," *Energy Research & Social Science* 19 (2016): 66–93.

3. Mark Cooper, "Why Growing Up is Hard to Do: Institutional Challenges for Internet Governance in the 'Quarter Life Crisis' of the Digital Revolution," *Journal on Telecommunications and High Technology Law* 11 (2013).

4. Elinor Ostrom, "Beyond Markets and States: Polycentric Governance of Complex Economic Systems," in *La Prix Nobel*, ed. Karl Grandin (Stockholm, Sweden: Nobel Foundation, 2010), 435–436. The policy challenges that Ostrom derives from her work on common pool resource systems are the challenges that the Parties to the Paris Agreement face. "Extensive empirical research leads me to argue . . . a core goal of public policy should be to facilitate the development of institutions that bring out the best in humans. We need to ask how diverse polycentric institutions help or hinder the innovativeness, learning, adapting, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales."

5. http://climatecommunication.yale.edu/visualizations-data/ycom/, http://climatecommunication.yale.edu/publications/update-supreme-court-suspends-clean-power-plan-yet-61-of-public-in-the-stat/.

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