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Abstract

Satellite solar power (SSP) has been suggested as an alternative to terrestrial energy resources for electricity generation. In this study, we consider the market for electricity from the present to 2020, roughly the year when many experts expect SSP to be technically achievable. We identify several key challenges for SSP in competing with conventional electricity generation in developed and developing countries, discuss the role of market and economic analysis as technical development of SSP continues during the coming years, and suggest future research directions to improve understanding of the potential economic viability of SSP.

Key Words: energy economics; solar power; space; satellites

Contents

Preface and Acknowledgments

In 1998, the National Aeronautics and Space Administration (NASA) asked Resources for the Future (RFF) to undertake a study of the economics of satellite solar power (SSP), a technology for collecting solar energy and sending it to Earth as a source of terrestrial electricity. The study was to look at SSP economics around 2020, when many experts expect SSP to be technically achievable. Our daunting task was to characterize the market for electricity during that future period. We were to identify key challenges for SSP in competing with conventional electricity generation in developed and developing countries, discuss the role of market and economic analysis as technical development of SSP continues in the coming years, and suggest future research directions to improve the understanding of the potential economic viability of SSP.

In separately funded research during this time, NASA convened experts from universities, government, and industry to study the technical design of SSP. Our economic study was to proceed independently from the technical research, although the information from the economic and technical analyses was shared periodically during several joint meetings during the study period. Such dialog among economists and engineers at an early stage of technology development was unusual, and both parties benefited from an improved understanding of SSP.

The economic study team included RFF scholars and experts from the energy industry. The team members of what became known as the Independent Economic and Market Assessment study are also the authors of this report. Their affiliations at the time of the study were as follows:

Joel Darmstadter, Resources for the Future

John N. Fini, Strategic Insight, Inc.

Joel S. Greenberg, Princeton Synergetics, Inc.

Molly K. Macauley, Resources for the Future

John S. Maulbetsch, Energy Power Research Institute

A. Michael Schaal, Energy Ventures Analysis, Inc.

Geoffrey S. W. Styles, Texaco, Inc.

James A. Vedda, Consultant

During the eighteen-month study, the authors met several times with other experts to discuss specific aspects of the SSP market. We are grateful for the information and viewpoints shared with us in briefings by these individuals:

John F. Ahearne, Sigma Xi (formerly with the U.S. Nuclear Regulatory Commission)

Jan A. J. Stolwijk, Department of Epidemiology and Public Health, Yale University School of Medicine

Gary Payton, U.S. National Aeronautics and Space Administration

Dallas Burtraw, Resources for the Future

Michael A. Toman, Resources for the Future

James Bond, The World Bank

Yves Albouy, The World Bank

Their perspectives have greatly enriched our study, and we hope that we have done justice to their contributions.

In addition, John Mankins, Joe Howell, and Neville Marzwell of NASA; researchers at Futron Corporation; and Don Crocker, our research assistant, provided significant assistance in locating additional reservoirs of expertise and serving as sounding boards during many of our discussions. John, Joe, and Neville provided this information while fully respecting and honoring the independent perspective of our study. Other officials at NASA, experts on the technical teams studying SSP, and colleagues in the space policy division at the University of Colorado also gave us useful comments during various briefings we made to them on our study.

We also thank Kay Murphy at RFF, who was the backbone of our effort in supporting the logistics of our briefings and the production of this report.

Final responsibility for the results and conclusions of this study rest, of course, with us alone.

Executive Summary

Satellite solar power (SSP) has been suggested as an alternative to terrestrial energy resources for electricity generation. In this study, we consider the market for electricity from the present to 2020, roughly the year when many experts expect SSP to be technically achievable. We identify several key challenges for SSP in competing with conventional electricity generation in both developed and developing countries, discuss the role of market and economic analysis as technical development of SSP continues during the coming years, and suggest future research directions to improve the understanding of the potential economic viability of SSP.

We find that several trends from the present to 2020 should influence decisions about the design, development, financing, and operation of SSP. One important caveat associated with our observations concerns the challenge of looking ahead two decades. We base our observations on what we believe to be plausible estimates of several key indicators derived from the work of respected national and international research groups, the information and perspectives shared by the experts we consulted for the study, and our own judgment. Although we believe this information is a valid basis for considering the competitive environment for SSP, we urge readers to appreciate the pragmatic process and somewhat intuitive elements involved in its estimation.

Our first set of observations concerns the market for electricity, particularly the key attributes of this market that are most relevant to investment in SSP:

- Current trends indicate increasing global demand for energy in general, and electricity in particular, during the period 2000–20. Electricity demand growth rates will vary significantly by region of the world and by stage of economic development. The highest growth will be in developing economies.
- Deregulation of electricity internationally will strengthen the trend toward decentralized, private ownership and management of utilities in most countries (developed and developing)—a major departure from the tradition of nationalized utilities.
- Nevertheless, the investment in and the operation of conventional electricity markets in developing economies likely will continue to be or will be perceived to be as risky as previously because of capital constraints, infrastructure limitations, and institutional and environmental factors.
- Constant-dollar electricity generation costs in 2020 likely will be no higher than prevailing recent levels and very probably will be significantly lower.
- The monetary value of environmental externalities in electricity generation appears to be significantly less than some studies have indicated.
- Global climate change is not presently a major factor in power investment decisions in developing countries. Willingness to pay for “clean” technologies tends to rise with increasing incomes, but in developing countries, clean energy may not rank highest among health and environmental concerns.

- Resource constraints on fossil fuels are unlikely to be a factor in this time frame, other than possible short-term supply disruptions caused by political and economic factors.

Taken together, these observations suggest that conventional electricity generation in both developed and developing countries may be more than adequate in terms of cost, supply, and environmental factors.

Our second set of observations pertains specifically to challenges facing SSP:

- The relative immaturity of the technologies required for SSP makes it difficult to assess the validity of estimated costs and the likely competitiveness of SSP. For this reason, as in many space development initiatives, orders-of-magnitude reductions in the costs of space launch and deployment and other key technologies are critical. As these reductions occur, the economic viability of SSP may become more promising. Until then, it is premature for the U.S. government to make commitments such as loan guarantees or tax incentives specifically for SSP.

- State-of-the-art conventional power-generation technologies increasingly incorporate numerous environmental controls, eroding somewhat the environmental advantage of alternatives to fossil fuel technologies, such as SSP.

- Actual and/or perceived health risks associated with exposure to electric and magnetic fields generated by SSP are likely to be of significant public concern.

- National security and national economic considerations may discourage some countries from participating in an SSP system operated by another country or group of countries. Countries with these concerns may require equity participation in SSP, limit their reliance on SSP to only a small share of their energy portfolio, or decline use of the technology altogether.

These findings argue for the merits of pursuing research and development in technologies required not only for SSP but also for other space activities, and for special consideration of issues that transcend the technical design of SSP, such as health and national security concerns.

We also urge economic study to continue hand-in-hand with SSP technical design. During the course of our study, we shared our interim findings with the engineering teams working on SSP. All parties agreed that this interchange of ideas was mutually beneficial and contributed markedly to deepening our collective understanding of next steps for both the technical team’s engineering studies and our economic analysis. The two must proceed in tandem, we all agreed, and specific recommendations for further economic and market studies include the following:

- The energy industry should be invited to be “at the table” in technical and economic analysis of SSP—that is, to both participate in conducting the analysis and learn about the results. The electric utility industry may be particularly interested in helping to guide the development of SSP technical components that also can be applied in other terrestrial commercial power markets (for example, the development of solar cells).

- Modeling of the economics of SSP should explicitly incorporate analyses of risk and uncertainty, include marketplace data about competition from terrestrial energy markets, and provide a means for structuring an efficient long-term technology development program that includes industry participation.

- Continued public funding of SSP for terrestrial power markets must consider the relative return on taxpayer investment in SSP compared with other technologies in general, and energy technologies in particular (for instance, photovoltaics). It should be noted that some past projections of large market penetration of new power-generation technologies (for example, nuclear and solar) have not been borne out by actual experience.

Finally, we identified specific topics for future research:

- Our focus in this report is on the use of SSP in terrestrial markets. SSP capabilities may be applicable to nonterrestrial systems, such as the International Space Station, other large orbiting platforms, lunar bases, and other activities that are used to explore and develop space. The benefits and costs of these opportunities should be investigated in the course of future SSP analyses.
- Real and perceived safety, health, and environmental risks associated with SSP in its terrestrial and nonterrestrial power markets should be assessed and discussed in public forums that engage both scientists and the public.

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Satellite solar power (SSP) is a means of collecting energy from the sun and transmitting it to Earth to provide electricity. An SSP system includes an orbiting platform, which gathers solar energy; a transmission system to send the energy to Earth; and a receiving antenna on the ground to collect the energy and convert it to a form usable by electric utility grids (see Figure 1). SSP has been suggested as an alternative to fossil fuels and nuclear fuels for electricity generation and also has advantages over terrestrial solar power because the satellite system can be continuously exposed to intense sunlight.[1]

The original concept for SSP was described more than thirty years ago by Dr. Peter Glaser of the consulting firm Arthur D. Little, Inc.[2] A decade later, the U.S. Department of Energy studied SSP and developed what became known as the 1979 Solar Power Satellite (SPS) Reference System. Although it was deemed technically feasible, the system assumed a very costly means of SSP deployment and operation (for example, a dedicated launch service infrastructure). As a result, most research on SSP by the U.S. government was halted by 1981. Since then, independent researchers have questioned the technical and economic assumptions of the 1979 SPS Reference System. They have proposed alternative development, construction, and operation scenarios that significantly reduce the costs and timeline for SSP deployment. Most recently, the National Aeronautics and Space Administration (NASA) 1995–96 Fresh Look Study identified several alternatives.[3] These alternatives include various system designs and orbital arrangements, some of which envision power delivery to locations in space as well as on Earth.

Economically viable SSP systems have not yet been developed, but advocates believe they someday could serve both industrialized nations and developing nations as a source of electricity. At present, the high risk, high cost, and long time horizon of SSP development and commercialization discourage private companies from mounting their own efforts to be first to market with this unconventional power source. Indeed, the view twenty to thirty years hence—when SSP is projected to be operating—is clouded by uncertainties. These uncertainties include future demand for and competition in conventional and alternative energy production; the extent to which environmental concerns associated with fossil fuel combustion may favorably influence decisions about solar-based technologies; and general perceptions of SSP that run the gamut from an individual's concern about the health and safety effects of its electromagnetic field to, perhaps, a nation's concern about whether

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[1] See Mankins 1998 for an introduction to and general discussion of SSP.

[2] Glaser 1968; a later study is by Econ, Inc. 1977.

[3] Feingold and others 1997.

SSP could be a reliable and secure source of energy. In addition, of course, and aside from these market-related factors, the construction and operation of SSP itself require tremendous technological achievements, such as much cheaper access to orbit and progress in robotic assembly and maintenance of structures in space.

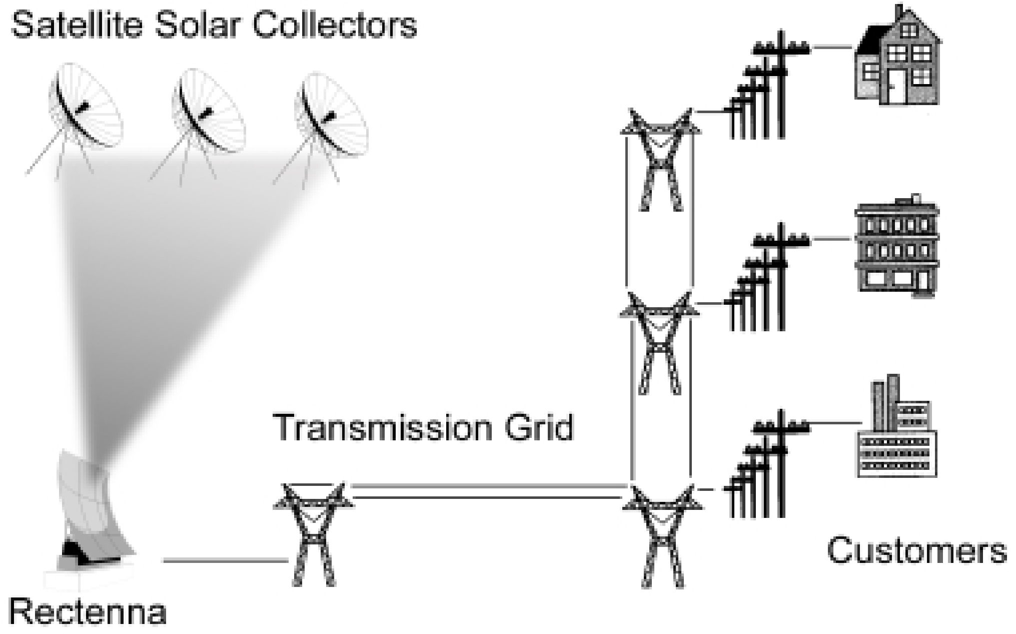

Figure 1. Illustration of Satellite Solar Power (SSP)

In 1998, NASA commissioned this report—an assessment of the economics of SSP as a source of electricity in terrestrial markets. Our study attempts to pierce the fog of economic and market uncertainty for decisionmakers and others interested in the possibilities of SSP in supplying this market. Our purpose is neither to advocate nor to discourage further investment in SSP but to provide a framework by which to gauge its economic feasibility if such investment continues. Our framework might best be thought of as an outline with "placeholders" for information as 2020 approaches. The data with which we parameterize our thinking in this study represent our best guesses and those of the experts we consulted. We encourage further peer-reviewed systems modeling of SSP that incorporate technical design and economic and market information, and we strongly feel that technical planning should be responsive to the implications of market and economic analyses.

We organize our observations and conclusions into identification of both opportunities and challenges for SSP in competing with terrestrial electricity generation. In Sections I and II, which constitute the bulk of our research, we provide a broad perspective on the market environment against which SSP would need to compete, roughly in the time frame 2015–20. Our primary focus is on long-term projections of conventional electricity generation, encompassing both the demand for and supply of electricity in industrialized and developing nations. Because SSP may best serve developing economies, we consider also on the investment climate that may likely characterize these nations in coming decades.

Also in Sections I and II, we address several related issues. We discuss the likelihood and potential effects of limits on the supply of conventional fuels (such as oil) on the economics of SSP, and whether SSP may have advantages over fossil fuels in reducing greenhouse gas emissions or in serving as an “insurance” premium in providing energy security. In addition, we briefly consider the health, safety, and environmental issues associated with the technology that may limit its public acceptance, such as the risk—actual or perceived—that may be associated with the electromagnetic field in the vicinity of SSP ground stations. Experts with whom we discussed this issue urged that any such real and perceived safety, health, and environmental risks should be assessed and discussed further in public forums that engage both scientists and the public as investment in SSP proceeds.

Although our charge was not to model the economics of SSP in significant detail, in Section III we offer some recommendations on desirable attributes of highly detailed economic models being developed by other researchers (such as those conducting follow-on studies to the 1996 Fresh Look analysis). Specifically, we address ways to frame the significant uncertainty associated with not only markets in the year 2020 but also technological developments required for SSP to bear fruit.

In Section IV, we briefly discuss the roles of government and the private sector in further investment in SSP. We suggest that decisions about continued public funding consider the relative return of SSP compared with other energy technologies (such as photovoltaics and fuel cells). We also note that past projections of large market penetration of new power-generation technologies (for instance, nuclear and solar power) have not, for various reasons, been borne out by experience. With this in mind, and given the large uncertainty associated with many of the technological breakthroughs needed for SSP deployment, we find that it is premature for government to make commitments such as “anchor tenancy,” loan guarantees, or tax incentives for SSP.

We also underscore the role of the private sector in planning SSP. For example, the electric utility industry should be invited to be “at the table” in technical and economic analyses—that is, to both participate in conducting the analysis and learn about the results—particularly because industry may be interested in helping to guide the development of SSP technical components that also can be applied in other commercial markets (such as solar cells). In addition, trends toward electricity deregulation argue for the private sector, not the government, to be the ultimate manager and operator of SSP, were it to come to fruition, and these trends are likely to have implications for the design of SSP.

Finally, in Section V, we recognize but do not explore what might emerge as a significant opportunity for SSP—namely, a source of electricity for space-based activities (such as the International Space Station and communications and remote sensing satellites). We recommend that future research consider these applications.

I. Global Electricity Markets in the Next Twenty Years: The Broad Economic Setting

In this section, we describe our perspective on the market outlook for terrestrial power in the time frame 2015–20, the market in which satellite solar power (SSP) would need to compete. Long-term projections, even of conventional electricity generation—much less of innovative systems—are inherently uncertain because they are conditioned by a vast number of debatable economic, technological, and policy assumptions. Our projections are thus best viewed as a road map from which numerous detours are not only possible but almost inevitable, because changing real-world developments serve to change one or more assumptions. (Just one of many such possibilities is that an international regime of severely curtailed carbon dioxide emissions could have major impact on electricity generated from fossil fuels.)

Nonetheless, we believe that our economic framework constitutes a starting point for weighing the commercial prospects for SSP. We focus on *baseload* power, although it is conceivable that SSP might serve nonbaseload markets. For example, SSP could provide extra power to meet seasonal demand or backup supply in the event of a power outage (see Box 1). However, we emphasize that many of the challenges we identify for SSP characterize both baseload and nonbaseload markets.[4] Our discussion in this section proceeds along general lines, and we substantiate our conclusions by more detailed spreadsheet analyses, which are described in the Appendix.

In the following sections, we describe the economic setting for global electricity markets in the next twenty years, then note methodological and data limitations that hinder the forecasts of these markets. With these gaps in methods and data in mind, we offer reasoned speculation about projections of electric capacity and generation as well as generation costs. Our emphasis is on costs, not prices (see Box 2), because prices can markedly deviate from costs as a result of tax policies, energy subsidies, and a host of other factors unrelated to costs. In other words, our goal is to enable an "apples to apples" comparison in estimating the costs of the technologies with which SSP would compete. We also note in our discussion some specific attributes of developing country energy markets, because they may be fertile markets for a prospective SSP system (we return to more detailed discussion of these markets in Section II). In addition, we briefly discuss the resiliency of our projections to resource constraints (for example, whether we are running out of oil) and to such potentially significant events as a global economic downturn.

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[4] Baseload power is the power provided by a system that operates essentially continuously and furnishes the minimum amount of power required by its customer. It is distinguished from peak power, which typically is provided by low-efficiency, high-cost systems operated only to meet demand in excess of baseload capacity.

Box 1. Other Potential Terrestrial Electricity Markets for SSP

Our analysis of the economic viability of SSP assumes that SSP would compete only with baseload power. SSP could serve additional markets; however, we doubt that these markets alone would economically justify the system. As noted in the NASA Fresh Look study (Feingold and others 1997), an SSP power plant could potentially provide peak load power quickly to several different markets, for limited periods each day. Other experts have noted that SSP also could offer seasonal sharing of capacity among regions or provide backup supplies in case of unit outages elsewhere in the local grid (referred to as "spinning reserve" in the industry).

The flexibility of SSP to serve these additional markets is largely due to two technological attributes. One attribute is that a disproportionately large percentage of the capital costs of the system is in orbit rather than in the relatively simple ground system. The second is that the beamed power can be directed at multiple ground stations at varying power levels, and power levels can be increased from zero to full power in less than one second.

We note that by the time SSP is deployed, technological innovation in other electricity supplies—for example, advanced storage systems—might compete with SSP in these markets. Also, increased construction, operation, and maintenance costs associated with an SSP system that serves multiple markets (such as the ability to redirect beams) must be considered in estimating the net advantage of SSP compared with alternative technologies serving these markets.

Box 2. Costs versus Prices

In determining the market situation SSP may face, we focused our study on forecasts of generation costs. The cost forecasts attempt to predict the expense of electricity generation, not the prices that final consumers of the electricity will pay.

Costs of electricity generation are the expenses incurred to create electricity. These expenses include capital and interest payments, operation and maintenance, fuel costs, taxes, depreciation, and a return on investment.

Prices are the expenses incurred by the users of the electricity. In addition to the generation costs, they include the expenses related to transmission and distribution, additional taxes, and, in some cases rate structures designed to discourage or encourage electricity consumption during certain hours of the day.

Conceptual and Methodological Issues

The ideal conceptual and methodological estimation of future global electricity demand and supply would incorporate myriad exogenous and endogenous factors: demographic and economic growth, a comprehensive energy framework that singles out electricity relative to other energy forms, technological options for generating electricity, and demand-and-supply schedules that determine the equilibrium cost and price at which transactions will occur. The model would allow for possibly important feedback loops and multidirectional cause-and-effect paths (for example, economic growth stimulates electricity demand, electrification stimulates economic growth) among these elements.

Such models exist for some individual countries—for example, the U.S. Department of Energy's (DOE) National Energy Modeling System (NEMS) for the United States—but even they are still evolving in terms of their reliability and refinement. To our knowledge, no model that binds individual country projections together into a consistent global aggregate has ever been constructed in anything other than perhaps a highly stylized and abstract formulation. For example, in its coverage of regions that are not members of the Organisation for Economic Co-operation and Development (OECD), the International Energy Agency (IEA) "does not explicitly take account of electricity generation economics."[5]

The practical consequence of this gap is that, for the purposes of this study, we present what we believe to be plausible estimates of several key indicators derived from the work of respected national and international research groups. Although we believe this information is a valid basis for considering the competitive environment for SSP, readers need to keep in mind the pragmatic process and somewhat intuitive elements involved in their estimation. One such caution relates to the fact that the following text discussion is conducted largely in terms of *point* estimates of projected indicators. Obviously, alternative assumptions regarding demographic, economic, and technological factors would yield a range of possible outcomes. Indeed, we conducted a limited analysis (summarized in the next section and elaborated in the Appendix) that characterizes various plausible future electric generation technologies in the United States and the range of costs associated with each. Our more general estimates are generally consistent with midpoints along the ranges indicated in our detailed analysis.

Projections of Electricity Capacity and Generation

We tap several sources for forecasts of future electricity capacity requirements and electricity generation (or sales), notably, regular forecasts from the U.S. Department of Energy's Energy Information Administration (EIA) and the IEA, which is affiliated with the OECD. The World Bank also releases periodic projections for selected developing countries and regions. Although the scope of coverage and certain specific features of the analysis differ among these efforts, the trends of greatest interest for our purposes tend to be in agreement. The single most conspicuous, if intuitively obvious, point of agreement concerns the near certainty of markedly varying rates of growth—and, therefore, shifting regional distribution—of electricity markets around the world. These projections are predicated on a consistent relationship between economic growth and growth in the demand for energy in general, and for electricity in particular.

That expectation is strikingly reflected in several interrelated sets of data:

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[5] See IEA 1994, 268.

- Electricity generation in developing countries accounted for nearly 30% of the world total in 1996; by 2020, EIA projects that share to grow to around 40%. China and India alone show increases indicating that their shares will be 10–20%.[6]
- Over the 1995–2020 interval, IEA estimated new worldwide generating capacity requirements of nearly 3,500 GW, half of which is attributed to the needs of developing countries.[7]
- Average annual growth rates in electricity consumption for selected countries and regions show sharply contrasting trajectories over 1995–2020: United States, 1.2%; all industrial countries, 1.9%; former Soviet Union, 1.2%; China, 5.8%; India, 5.3%; all developing countries, 4.6% (see Table 1). These numbers are, of course, not preordained; thus, it is possible that under a relatively low price regime, U.S. electricity demand will grow more than the posited 1.2% (see Box 3).
- With economic growth, electricity progressively becomes the preferred form of energy—both to provide creature comforts and to meet the needs of a more diversified and sophisticated industrial structure. Thus, across OECD countries, energy consumption accounted for by the electric power sector increased from more than 20% in 1971 to 35% in 1991 and is projected to reach 40% in 2010. The corresponding percentages for China at these three benchmark years are around 15%, 20%, and 30%.[8]

In Section II, we return to discussion of these market trends in developing countries, specifically with respect to the investment climate that might be expected for new energy initiatives such as SSP and other technologies. In general, however, determining the likely future trend in electricity capacity and consumption is anything but straightforward—for the developed or the developing world. With a “bottom-up” approach, discrete attention would need to be accorded to the technological, engineering, and economic factors that govern electricity use in specific sectors of the economy, such as extractive industries, manufacturing, residential and commercial structures, and transportation. With the much more collapsed “top-down” perspective—adequate for present purposes—the principal determining factors are the assumed growth in gross domestic product (GDP) (or income). Other factors are the income elasticity of demand, which describes the change in electricity demand accompanying the change in GDP—a relationship that subsumes both behavioral and technological factors—and changes in the relative price of electricity.

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[6] See EIA 1998b.

[7] See IEA 1998.

[8] See IEA 1994.

Table 1. World Total Net Electricity Consumption and GDP Growth by Region, Reference Case, 1995–2020.

Region/country	*Electricity consumption (billion kWh)*								*Change/year, 1995–2020 (%)*	
	Actual			*Projected*					*Consumption*	*GDP*
	1990	*1995*	*1996*	*2000*	*2005*	*2010*	*2015*	*2020*		
Industrialized countries										
North America	3,255	3,759	3,859	3,984	4,347	4,713	5,050	5,354	1.4	2.1
United States[a]	2,713	3,163	3,243	3,318	3,601	3,877	4,115	4,308	1.2	
Canada	435	462	473	499	528	574	625	680	1.6	
Mexico	107	134	144	167	217	261	310	367	4.1	
Western Europe	2,115	2,286	2,330	2,720	3,064	3,419	3,781	4,182	2.4	2.4
Industrialized Asia	930	1,068	1,090	1,263	1,393	1,531	1,666	1,812	2.1	2.3
Japan	750	864	882	976	1,063	1,162	1,258	1,363	1.8	
Australasia	180	204	207	287	330	369	407	450	3.2	
Total industrialized	**6,299**	**7,133**	**7,279**	**7,968**	**8,804**	**9,663**	**10,497**	**11,349**	**1.9**	**2.3**
FSU/Eastern Europe										
FSU	1,488	1,168	1,133	1,108	1,236	1,366	1,472	1,586	1.2	3.6
Eastern Europe	420	384	401	401	449	515	584	662	2.2	4.4
Total FSU/E. Europe	**1,908**	**1,552**	**1,535**	**1,509**	**1,685**	**1,881**	**2,056**	**2,248**	**1.5**	**3.7**
Developing countries										
Developing Asia	1,268	1,912	2,002	2,489	3,283	4,160	5,255	6,665	5.1	6.2
China	551	881	925	1,076	1,476	1,975	2,657	3,574	5.8	7.9
India	257	367	378	541	706	888	1,092	1,344	5.3	
Other Asia	460	663	699	872	1,101	1,297	1,505	1,747	4.0	5.2
Middle East	221	295	301	309	362	419	483	554	2.6	3.8
Africa	285	320	332	378	459	552	657	782	3.6	4.1
CA and SA	449	575	604	711	902	1,088	1,290	1,548	4.0	4.3
Brazil	229	288	303	371	497	637	813	1,039	5.3	
Other CA and SA	220	286	301	340	406	451	477	509	2.3	
Total developing	**2,224**	**3,102**	**3,239**	**3,886**	**5,007**	**6,220**	**7,684**	**9,548**	**4.6**	**5.2**
Total world	**10,431**	**11,767**	**12,053**	**13,363**	**15,495**	**17,764**	**20,237**	**23,145**	**2.7**	**3.1**

Notes: Based on reference-level GDP forecast. Electricity consumption equals generation plus imports minus exports minus distribution losses. FSU = Former Soviet Union; CA, Central America; SA, South America.

Sources: For actual values, EIA (1998b, Table 6-2); for projected values, EIA (1997a, Table A8; 1997b).

[a] Includes the fifty states and the District of Columbia. U.S. territories are included in Australasia.

Box 3. Are We Running Out of Oil?

A recent article in *Science* magazine contained only the latest in a long line of prognoses that go back 100 years, in which oil's near-term "exhaustion"—a concept bereft of economic logic—is viewed with near inexorable certainty (Kerr 1998; see also the response by Toman and Darmstadter [1998]). During the first half of the twentieth century, a succession of assessments by analysts and officials of the U.S. Geological Survey predicted a peaking in U.S. oil production and, effectively, its exhaustion within one or two decades of the date of the forecast. Then, Ayres and Scarlott (1952), whose point of departure was a 1950 estimate of proved world oil reserves of 78 billion barrels, predicted that future discoveries would sustain cumulative production of 550 billion barrels at most. In fact, by the end of 1997, proved global reserves stood at a trillion barrels, and cumulative production since 1950 totaled 756 billion barrels (BP's *Statistical Review*, various years; EIA's *Annual Energy Outlook*, various years). Kerr's article cites five (of six) recent studies that predict a peaking in world oil production by 2020. Although such studies follow a long-established pattern of alarm over resource scarcity, an equally well-established (though perhaps not as sensational) body of literature questions that perspective. One effective refutation of the scarcity thesis, for example, is contained in numerous writings of M. A. Adelman, now a professor of economics emeritus at MIT and undeniably, throughout his career, one of the most astute analysts of the world oil market and the dynamics of oil reserve development and estimation. (For a recent retrospective account of his views, see Adelman 1997, 13–46.) We simply note three fundamental points bearing on this issue:

- There has been a persistent failure to distinguish between the concept of proved, recoverable reserves—which firms tend to view as their "on-the-shelf" inventory for commercial planning horizons—and that of discoverable resources, which, partly in response to long-term price expectations and with opportunities for technological innovation, warrant investment and exploitation over a much more distant time span.
- Technological progress—admittedly an elusive factor to predict and quantify—can offset poor geological prospects. Thus, the onset of three-dimensional seismic exploration, horizontal drilling, and the development of resources at ever greater ocean depths during the past several decades promises to undergird production prospects that few would have predicted twenty-five years ago.
- Most telling of all, it is a matter of recorded fact that, notwithstanding periodic episodes of short-term volatility (including the price run-up during the 1970s, the ensuing price slump, and the current escalation), long-term oil prices held steady throughout much of the twentieth century—a trend entirely consistent with an unfolding supply picture that has unfailingly undermined predictions of running out. Those who believe that a genuine discontinuity in oil resource availability is now imminent face another logical paradox: Why would numerous companies and countries holding increasingly scarce resources be content to sell those assets at fire sale prices rather than managing their disposition in a revenue-maximizing way that capitalizes on the inexorable price rises that some analysts see as inevitable? To be sure, some ("high discount") countries may be so hard-pressed for cash as to ignore an economically more rational time path for managing their reserves. (A still useful discussion of factors affecting discount rates of oil-producing countries is presented by Bohi and Russell [1975, especially 45–54].) Turmoil in Nigeria could, for example, bring about such a policy. It also is conceivable that, at some point, fear of "technological obsolescence" of oil in the ground, because of restrictions on the use of carbon-containing fuels, would cause producers to accelerate production and deter aggressive reserve development. But, as best as one can judge from a present vantage point, it is hard to imagine that purposefully rapid depletion of reserves is endemic among oil producers.

Note that according to Table 1, to varying degrees throughout the world, electricity demand growth lags GDP growth. The lag would most likely be still greater without the assumption of stable real cost and price (discussed in the next section). Thus, slower electricity demand growth (relative to GDP growth) reflects the widespread potential for enhanced efficiency in the application of electricity in different activities. The countries of the former Soviet Union are particularly conspicuous candidates for such improvement. Although EIA's underlying analysis (for the estimates shown in Table 1) is sketchy, one can assume that the elimination of controlled prices and retreat from a rampantly mismanaged energy system that invited huge waste are key reasons for projection of the region's relatively slow electricity growth.

Other factors may impact demand. For instance, the current direction of information and communication technology could conceivably result in a substantial "decoupling" of economic growth and energy demand growth, at least in the developed economies. We largely exclude this possibility from our analysis. In addition, opportunities for achieving greater efficiency exist as well in the *production* of electricity. For example, the IEA projects important gains both in China's conversion of fuels into electricity (the so-called heat rate) and in the capacity utilization of the country's installed generating capacity. If these developments come to pass, then the challenges to the competitiveness of SSP significantly increase.

Cost of Electricity Generation

Analysis of SSP's ability to compete with terrestrial electricity generation obliges us to make estimates of comparative electricity production costs over a time frame of fifteen to twenty-five years. Unfortunately, current—let alone projected—terrestrial generation costs are hard to come by, particularly for those countries or regions that, by virtue of size and electricity demand growth, are likely to constitute the most promising markets for SSP. This state of affairs exists even though the capacity and generation estimates cited earlier must embed some necessary relationship, however unspecified, to cost and price.

If delivered energy *prices* in such markets could reasonably be taken to be based on cost of service, with minimal distortion arising from subsidies and other regulatory intrusion, one could perhaps work back from prices to approximate costs. But such a tack is likely to prove futile for many situations in developing countries (or transition economies). Anderson (1997) cited surveys that showed generating (that is, busbar) costs that frequently were twice the average tariff charged final consumers. In rural areas of many countries, the multiple is much greater still. Although designed to make electricity more affordable, such policies have resulted in deterioration of, and underinvestment in, electricity supply systems.

Accordingly, our approach to estimating projected electricity production costs in markets of primary interest was to exploit projections of U.S. generating costs as a basis for framing ranges of costs for other regions or countries. We took this approach for several reasons:

- Deregulation of foreign electric power markets would in itself narrow international cost differentials. This trend already has been suggested by recent public bids for independent power projects (IPPs) in Japan and Thailand.

- Resource inputs (except for hydropower) trade in a world market that is increasingly characterized by world prices; it is true of oil and coal and may become the case more often with gas via long-distance pipelines of liquified natural gas (LNG; note, for example, the rising share of natural gas, shown in Table 2).

- Globalization of investment and technology (for example, the energy investments by Enron Corporation in India) would, at least directionally, contribute to convergence of cost.
- Given the diversity of energy sources that can be used to generate electricity, interfuel competition to serve the power market can help to hold costs down.

With the foregoing reasons in mind, we assume that nationwide U.S. generating costs for plants coming on line in 1996 averaged about 3.7 cents/kWh. This value is neither conceptually nor empirically an entirely "hard" number. Among the problems, the number reflects a mix of coal and other plants, whereas a long-term marginal cost estimate might revolve principally around combined cycle gas plants; also, elements of accounting cost may be intermingled with purely economic cost. But it probably can serve as a base year jumping-off point.

Projecting generation costs for 2020 is necessarily predicated on a multiplicity of assumptions, different combinations of which yield numerous alternative cases. The assumptions include the prices of resource inputs to power stations, heat rates, capacity factors, the degree of deregulation in the electric utility market, capital costs for different technologies, and discount rates. The important point we recognize is that in almost no cases are constant-dollar generation costs in 2020 likely to be higher than prevailing recent levels; they very probably will be significantly lower. This fact is reflected in EIA's reference case projection of *delivered* electricity prices: From 7 cents/kWh in 1996, they decline to 5.5 cents/kWh in 2020.[9] If we assume that transmission and distribution costs retain their present share of delivered electricity prices, a "reference case" decline in U.S. generation costs from around 3.7 cents/kWh in 1996 to around 3 cents/kWh in 2020 seems entirely reasonable.

A much more detailed spreadsheet analysis for the United States to estimate costs among an array of technologies helps to substantiate the forecasts and the reasoning underlying the foregoing paragraphs (as noted earlier, our calculations and assumptions are described in the Appendix). For fossil fuel–based technologies, we find cost estimates around 1.7–3 cents/kWh as a "low range" and some higher estimates as high as 10 cents/kWh. For renewable technologies, our range of estimates is considerably wider, from around 1.7 cents/kWh to as much as 54.5 cents/kWh. All things considered, we find that our ballpark figure of 3 cents/kWh is a good proxy for the technologies with which SSP will most likely have to compete (according to EIA, they are likely to be dominated by combined cycle gas and pulverized coal plants).

From this starting point, what might we prudently assume to be the largest realistic multiple for electric power production costs in developing countries? Such countries now are characterized by grossly distorted pricing structures, trade barriers, numerous transaction costs (for example, the formidable challenge of just setting up a customer billing system), and other investment disincentives. In contrast to the estimated U.S. generating cost of approximately 3.7 cents/kWh and on the basis of

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[9] Expressed in 1996 dollars; see Annual Energy Outlook (1998, 140).

informal discussion with several experts, we estimate that for the part of the world dominated by large markets in developing countries, present-day generation costs average around 5.5 cents/kWh. A recently released OECD report indicates that coal-fired plants in India and China scheduled to come on line during 2005–10 would generate electricity likely between 3.2 and 4 cents/kWh (expressed in 1996 prices.)[10] This downward trend portends significant competition for SSP from conventional technology.

Table 2. World Energy Consumption for Electricity Generation by Region and Percentage of Fuel Share, 1995–2020.

Region and fuel	*Fuel share (%)*	
	1995	*2020*
Industrialized countries		
Oil	6.7	5.3
Natural gas	10.5	23.4
Coal	35.7	33.3
Nuclear	25.1	13.9
Renewable resources	22.2	24.1
FSU/Eastern Europe		
Oil	11.3	14.6
Natural gas	38.3	53.2
Coal	27.4	15.8
Nuclear	10.9	0.0
Renewable resources	12.1	16.1
Developing countries		
Oil	14.0	11.2
Natural gas	12.4	17.5
Coal	43.9	45.7
Nuclear	3.2	6.4
Renewable resources	26.7	19.2
Total world		
Oil	9.4	9.0
Natural gas	15.9	24.8
Coal	36.4	36.3
Nuclear	16.7	8.9
Renewable resources	21.6	21.0

Note: Values represent EIA's Reference Case. FSU = Former Soviet Union.

Source: EIA 1997b.

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[10] See OECD 1998.

Resource Constraints?

The projections presented earlier assume that, for the period covered by our report, the supply and real cost of electricity will not be impaired by scarcer—hence, costlier—fuels needed by the power sector. The EIA has tested the implications of different world oil prices (which can serve as a general proxy for such global supply constraints) on electricity for the United States in 2020. It found that even a scenario in which a high world oil price in 2020 exceeded the "reference" case (which underlies the preceding discussion and the estimates of Tables 1 and 2) by 30% affects electricity sales and prices relatively modestly.[11] That outcome is explained by a shift to the use of coal and, in particular, natural gas—fuels whose abundance during the period in question and substantially beyond will keep electricity generation costs in check. To be sure, the fuel component of the cost of generation is not inconsequential. Therefore, recurrent anxiety about energy resource limits and their possible impact on electricity costs is understandable. At the same time, given this shift in fuel inputs at power stations, it is worth noting that the vastness of U.S. and global resources of coal should not be subject to dispute. Natural gas, too, is increasingly viewed as a sizeable resource. In terms of geological assessment, it is a relatively "young" resource whose exploitability stems from the feasibility of pipeline transport, which began only half a century ago, and ocean transport of LNG, which began still more recently. As a result, natural gas historically has been flared as uneconomic, with geographically limited exploration incentives until recently.

Of course, discussions of resource scarcity have centered most frequently on oil—historically, the most versatile of primary energy resources and the resource whose price has served as a rough benchmark for energy in general. However, it is an undeniable fact that a century of repeated predictions of the imminent disruptive prospects of oil scarcity have failed to materialize, even as real oil prices have remained stable over the long run. This record of misjudgment does not preclude an altogether different outcome for coal or natural gas in the decades ahead. But it does impose a burden of proof on analysts who dismiss lessons conveyed by this historical experience (see Box 3).

In brief, history is no certain guide to the future. The wolf that has so far failed to appear as predicted may still be lurking near the door. But it is not out of the question that constraints, if they are to appear, may come from quarters other than geologic tightfistedness. Four examples come to mind.

Environmental Concerns

Plausibly, severe environmental restrictions on combustion of fossil fuels could translate into an economic burden absent from the projections reviewed earlier. Although recent studies suggest that the damage (or "social cost") of electricity generated by conventional means may be relatively small—particularly for the noncoal resources likely to figure increasingly in future capacity additions (see Box 4)—the costs of *abatement* that some policymakers may propose could be less than or exceed that magnitude. Indeed, early and stringent constraints on CO_2 emissions could easily invite the second prospect. Issues of pollution, deforestation, and global warming are receiving growing attention by the world community. However, cleaner forms of energy have been introduced into the

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[11] See EIA 1997a, 7, 168.

developing world in numerous initiatives to ameliorate these problems, and some governments already have begun to use renewable energy technologies as a tool of economic development. For example, India, China, South Africa, and several other countries have begun to use renewable energy as a means of providing at least limited localized power to small communities without the cost of stringing power lines to rural areas. Increasing investment in this infrastructure will likely lead to an installed base with which SSP would have to compete.

Box 4. Fossil Fuels and the Environment: Estimates of the Social Costs

Advocates of SSP have suggested that it offers an attractive alternative to many conventional fuels as a source of electricity, in part because SSP would not contribute to air pollution or other health or environmental problems. However, an important finding of the most recent studies of the relationship between fuel cycles and health and environmental effects is that damages associated with new generation plants are surprisingly modest (see Krupnick and Burtraw 1996). The monetary estimates of the environmental and health damages, or "social costs," of electricity fuel cycles suggest the following:

Table B-1. Estimated Costs of Power Generation.

New plant type	*Cost (cents/kWh)*
Pulverized coal	0.1–2.0
Nuclear[a]	0.03
Gas[b]	0–0.1
Oil	0–1.5
Biomass	0.2–0.4

Note: The estimates for nuclear power include engineering estimates of accident probability.

[a] Pressurized water reactor.

[b] Combined cycle gas turbine.

To these estimates might be added the damages associated with greenhouse gases and their relationship with global climate change. Several studies have attempted to make some very tentative estimates of the long-term effects of increases in CO_2; the monetized value appears to be on the order of 0.3–0.6 cents/kWh, assuming a discount rate (to take into account the long-term effects) of 3%.

Taken together, these estimates imply that the "bottom line" based on the most recent research on monetized damages—and given the numerous caveats which the researchers are the first to acknowledge—is on the order of 2 cents/kWh. To the extent that requirements for new power plants are not met, developing countries will continue to meet energy needs by burning biofuels, operating antiquated power plants, and attempting to integrate renewable energy systems into their economies. However, concerns about air pollution or its contribution to global climate change are not presently a major factor in power investment decisions in developing countries, although local pollution problems in large cities such as Mexico City may cause countries to favor nonpolluting technology. Willingness to pay for clean technologies tends to rise with rising incomes; however, in developing countries, clean energy may rank as a somewhat lower (although related) priority than clean water, improved sanitation services, and health care.

Other Health and Safety Concerns

SSP itself may have associated with it sources of potential actual or perceived health and safety risks, such as those that may result from the electromagnetic field (EMF) around its ground stations. One expert with whom we consulted emphasized that few epidemiological data are available to understand the effects on health of the power levels that are likely to be associated with SSP. Moreover, he pointed out that reliable data are difficult to obtain because they require the exposure of a large population for long duration. Additionally, monitoring protocols at international and national levels of government have yet to be established for beam power densities such as those of a system like SSP. He also emphasized that even if health and safety risks were negligible or manageable, public perception of such risks would likely figure prominently in their acceptance of SSP.[12]

Unusually High Demand Growth

A third possibility is that a sustained period of unusually high economic growth could strain the ability of current resources to meet the resulting energy demand at given real prices. As we suggest in Box 1, this situation could conceivably open up a promising niche market for alternative energy sources, including ones for use in electricity generation. Much would depend on how enduring that strain turned out to be; “alternative” energy projects initiated in the 1970s with the expectation of prolonged high and rising energy prices experienced substantial disappointment.

Perceived Risks of Energy Import Dependence

Finally, the perceived risks of dependence on imported energy could lead to support for policies of greater self-sufficiency—leading, in turn, to higher electricity costs or alternative sources of electricity. The case for protectionism is far from clear, conceptually or empirically.[13] Still, despite OPEC’s conspicuous failure to sustain any extended control over the world oil market after its short-lived success in the 1970s (and recent supply manipulation), the possibility that exploitable oil resources will be disproportionately concentrated in few enough countries so as to invite more effective cartelization, thus contributing to a long-term run up of other energy resources, cannot be totally dismissed.

Somewhat parenthetically, we note that the question of energy dependence may present a rather unique challenge in the context of an SSP regime. A country fueling its power plants conventionally has a choice of fuel mixes and diversified geographic supply sources that ensure some considerable resilience to the economic shock of a disruption. By contrast, a developing country reliant on another country’s space-generated power for a significant portion of its baseload electricity may enjoy little such flexibility. It therefore may look to equity participation in an SSP system, seek other means of protecting itself against the potential discontinuity of external supply, or possibly reject SSP out of hand even if SSP made economic sense. This issue deserves a close look.

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[12] Anderson 1998 has begun to outline an approach to considering these issues in the case of SSP.

[13] A detailed treatment of this issue appears in Bohi and Toman 1996, especially 18–27.

Postscript: The 1998 Global Economic Downturn

Long-term energy projections and the economic growth assumptions to which they are significantly related do not assume a linear path over the projection period. That is, average annual growth rates, such as those cited in the preceding section, have built into them the normal business cycle fluctuations historically characteristic of market economies. The question to ponder is whether the economic slowdown accompanying the financial and capital market upheavals that recently have roiled some parts of the world (particularly East Asia) is sufficiently abnormal as to cast doubt on projections even as distant as twenty to twenty-five years in the future. In other words, is it reasonable to assume that whatever stagnation has recently been experienced (particularly in East Asian markets) will be offset by higher-than-average growth during a recovery phase over the next few years—justifying the reference case projections in Table 1? And is it likely that selected policy retreats from free market processes (for example, in Malaysia, Russia, and Venezuela) are a temporary phenomenon unlikely to undermine longer-run prospects? This question is of particular interest, because the unfolding electricity picture we hypothesize is importantly predicated on the existence of policies and institutions in which energy choices can be exercised within a relatively unfettered domestic and global marketplace rather than hobbled by the persistence of various market distortions.

This study professes no basis for answering these questions, either reassuringly or pessimistically. Clearly, a lower economic growth trajectory also signifies slower electricity demand growth. In EIA's *International Energy Outlook 1998* (EIA 1997b), a slow economic growth scenario of 3.7% yearly is associated with 3.1% electricity growth; these values contrast with the 5.2% and 4.6% rates, respectively, for developing countries listed in Table 1.

But whichever of these scenarios seems more compelling, the present situation in global markets may be serious enough to inject a substantial degree of uncertainty into planning decisions for infrastructural projects as basic as electricity. For that matter, another study would need to judge the implications of abnormally *high* growth as well. After all, since around 1985, utility forecasts in the United States have been consistently higher than actual growth (see Box 5). In any case, greater uncertainty translates into greater risk, and greater risk translates into increased returns on capital demanded by investors—even for conventional energy projects, let alone for those of a more speculative nature.

Box 5. The Case for Higher U.S. Electricity Demand Growth

As indicated earlier, and as evident from Table 1, rather anemic electricity demand growth is forecast for the United States and the total of the industrialized countries (1.2% and 1.9% per year, respectively) (EIA 1998b). Are prospects pointing to significantly higher long-term growth in industrialized countries in the future? Historical actual and forecasted electric energy demand growth rates for the United States from a consistent industry source, the North American Electric Reliability Council (NERC), suggest that this could be the case (NERC 1998a). In no ten-year period from 1974 to the present did U.S. electricity demand drop below 2.2%. Although utility forecasts were consistently higher than actual growth until 1985, actual electric energy demand growth has been consistently underforecasted since then. In fact, the most recent NERC forecast has, for the first time, pointed out the issue of consistently low forecasts and the likely ramifications (NERC 1998b). In addition, technological innovation can create demand for electricity even faster than the expected improvements in efficiency and rising real income.

Several implications would follow if U.S. electricity demand growth were to increase at a higher rate than current estimates project. First, much more capacity would be needed, because a 2.4% average annual growth rate would increase electricity demand 124% of the projected 1.2% average annual growth rate. Second, any environmental control strategies that seek to limit U.S. electricity demand growth, directly or indirectly, would be more costly, with growth higher than that currently assumed as a baseline. Should such factors carry over into the experience of developed countries between now and 2020 or so, both industrialized and developing countries may be in search of additional electricity supplies.

II. Trends in Power Generation for Developing Nations

In Section I, we noted that two points of agreement among estimates of future electricity capacity and generation are the near certainty of markedly varying rates of growth and shifting regional distribution of electricity markets around the world. In this section, we address in somewhat greater detail the markets in developing countries.

Under current development trends, the cumulative capacity requirement for electrical energy will total some 3,500 GW between 1995 and 2020.[14] Of this total, only 30% (around 1,000 GW) will be in the OECD member industrial countries. The remaining 70% of capacity requirements (2,500 GW) will be split between China and other developing countries. In this context, the developing world consists of China, India, other developing Asian countries, the Middle East, Central America, South America, and Africa.[15]

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[14] IEA 1998.

[15] We do not incorporate the OECD's revised definition, which includes several of the higher-income developing countries.

According to some projections, China's requirement alone (about 1,740 GW) will surpass that of all OECD countries together. The remaining developing countries will require 700 GW of capacity. If these requirements were met, the developing world and China would consume approximately 40% of the world's electric energy production by 2020. But for these requirements to be met, some formidable problems must be overcome.

Financial constraints are foremost among these problems. Assuming an average installed capacity cost of around $900/kW to construct the capacity required by year 2020, total capital cost requirements would be slightly more than $3.3 trillion.[16] Of this amount, the developing world would require $2.3 trillion by 2020, or an average of $92 billion a year from 1995 to 2020 (translating into 97,300 MW per year of new capacity in the developing world). Record levels of foreign debt make it difficult for these countries to borrow additional funds for power projects. More than 70% of developing countries were net importers of energy in 1987 and paid for these imports with hard currency and hard currency loans that effectively reduced opportunities to deploy capital on infrastructure projects.[17]

In most cases, developing nations lack local equity markets and have smaller, less liquid debt markets that are characterized by shorter-term loans.[18] In addition, lending for power projects by multilateral lending institutions has decreased substantially from levels that were generally insufficient in the first place.[19] For instance, the World Bank currently provides roughly $3 billion annually for energy sector projects, a small fraction of the developing world's total expenditures.[20] In total, annual capital spending on power generation in the developing world is roughly $50 billion to $60 billion.

Independent power projects (IPPs) have been cited as a new source of capital for the developing world. In an IPP, private firms build power plants for individual customers and government agencies. IPPs financed more than $20 billion of new capacity in 1997, nearly $11 billion 1996, and around $9 billion in 1995.[21] However, in 1997, only 17,000 MW of new capacity was put under contract.[22]

A major factor influencing the willingness of lending institutions and IPPs to finance investment in developing countries is the perceived risk associated with unstable governments, economies, and currencies. Most developing countries are rated "noninvestment grade" (their loans will carry a higher interest rate). These loans reflect risk premiums ranging from around 100 to more than 200 basis points over benchmark floating interest rates derived from either the London Inter-bank Overnight Rate (LIBOR) or U.S. Treasury Notes. In addition, IPPs also carry other conditions designed to reduce risk, including guarantees of currency convertibility and protection in case of changes of law or regulatory regime; protection against financial market disruptions and fluctuations; guarantees of

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[16] IEA 1998.

[17] OTA 1992.

[18] Dailami and Leipziger 1997.

[19] EIA 1996b.

[20] United Nations, Commission on Sustainable Development 1997.

[21] Anderson and Burr 1997.

[22] Burr 1998.

interest, exchange, and tariff rates; and guarantees of debt and revenue.[23] The combination of higher interest rates and higher expected rates of return by the investors means that the average cost per kilowatt-hour is higher in the developing world than in the developed world if all other factors are the same. Host countries have been willing to agree to these conditions because few other financing options are available.

It is important to note that these trends affecting investment in the power industry reflect the overarching concern of financial markets about the general state of the emerging market economies. In an article in the *Economist,* a Goldman Sachs analyst predicted that net capital flows to developing countries could be $120 billion in 1999, down from $247 billion in 1997.[24] And according to the same article, even when the emerging markets eventually rebound, investors will be far more cautious: “The long-maturities, non-collaterised bonds and complex project-finance deals that characterized emerging markets will be out. Instead, investors will want bonds with short maturities—‘plain vanilla’ deals that are easy to sell if they again get cold feet.”

Investment also will be more difficult in countries that have not attempted to privatize the power sector and continue to subsidize this sector as a tool of national policy (in much the same manner that agriculture is subsidized). One effect of subsidies has been insufficient revenues to either maintain generation capacity or build new capacity. As noted earlier, the result has been power shortages that are exacerbated by industries and consumers using excessive amounts of electricity because of its artificially low price caused by subsidies. Taken together, these financial and institutional issues are likely to make power projects—including SSP—very difficult to fund in the developing world without some changes in the status quo.

III. Economic Modeling in Support of SSP Programmatic Decisions

Thus far, we have described the future market for power. In addition to this focus, during the course of our report, we had the opportunity to share methods and conclusions with the engineering working groups analyzing the technical design of SSP. The uniqueness of dialog among economists and engineers at an early stage of technology development prompts us to include here a brief discussion about the usefulness of this exchange of information. Accordingly, in this section we depart from discussion of electricity markets to focus on economic modeling in support of the SSP program.

Such modeling can shed light on the future marketplace in which SSP is likely to operate, providing key feedback for SSP design and engineering. One example is the importance of supply reliability and geographic coverage to electricity customers. These factors clearly bear on the technical design of SSP. Another example is the trend toward decentralized management and private-sector ownership and operation of electricity supplies. This factor, too, has implications for technical design.

Economic models also can establish the potential economic benefits to the nation that may result from a government investment in technology development and provide a formal means for structuring an

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[23] Dailami and Leipziger 1997.

[24] *The Economist* 1998.

efficient long-term, multiphase technology funding program. To date, detailed modeling of the economics of SSP has been limited in several respects (see Feingold and others 1997). The existing models of SSP might be improved to include formal use of uncertainty and risk analysis techniques or, as minimum, the use of *expected* values for the important variables. In addition, further exercise of these models might allow the implications of key assumptions—such as those related to the cost of robotic assembly, refurbishment and maintenance, and on-orbit operations—to be explicitly considered.

In using economic modeling to ascertain the potential national benefits of SSP, we caution against metrics of “job creation.” Jobs are more properly treated as a cost and not a benefit unless the nation’s unemployment rate is especially high.[25] Instead, we urge that consideration be given to the relative return on taxpayer investment in SSP compared with other publicly financed energy technologies (such as photovoltaics) and other more general taxpayer investments.

If future studies of SSP design suggest that it can be competitive with terrestrial energy sources and that reasonable benefits are likely to result from its development and use, then additional economic analysis will become useful in the planning and structuring of an efficient technology development and demonstration program. For example, a decision analytic approach could consider the economics of alternative mission designs, consider the possibility of failure and termination rules for SSP investment, and allow for data to be provided by experts that have disparate backgrounds (that is, no single research discipline—be it engineering or economics—may understand in depth the entire program).[26] To this end, SSP research should continue to involve interdisciplinary teams, convening regularly, with NASA sponsorship.

IV. Roles of Government and the Private Sector

Governments in the United States and abroad have become active in promoting many activities to foster the commercial development of space. Generally speaking, a host of factors may discourage private-sector financing of new technologies, such as large capital requirements, long lead times to commercial operation, lengthy payback periods, perceived high technical risks, and the inability to capture proprietary benefits of developing the technology. These hurdles have led governments to pursue, with mixed success, various programs and policies to underwrite commercial business ventures. For example, governments have funded or performed basic and applied research and development (R&D); established or encouraged the building of public infrastructure, such as roads, railroads, airports, and harbors; become early adopters or “anchor tenants” of new products and services, helping to establish the market; and enacted and enforced standards and regulations in areas such as safety and environmental protection. Cohen and Noll (1991) and Rose (1986) discuss these

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[25] See discussions of the problems of using jobs as a benefit measure of technology projects in, for example, Rose 1986, Cohen and Noll 1991, and CBO 1994; for a slightly different perspective, see Shaw and others 1998.

[26] An R&D simulation approach that was previously developed and may serve as a starting point is described in Hazelrigg and Greenberg 1991 and Hazelrigg 1992. See also Macauley and Austin 2000 for an approach to modeling sequential government investment in new technologies.

and other approaches to government intervention in the cases of commercialization of several technologies, including space activities. Box 6 illustrates some of these approaches.

Our view is that in the case of SSP as a source of terrestrial power, it is premature for government to make commitments such as anchor tenancy, cost sharing, low interest loans, or loan guarantees. SSP is at such an early stage of development that these options are inappropriate at this time. For example, anchor tenancy can significantly reduce market risk, but the government cannot enter into such an arrangement until a commercial entity has chosen a system design and committed to building it. For similar reasons, cost sharing is also premature; it requires agreement on system concepts and designs, a development timetable, detailed system cost estimates, and, above all, a well-grounded expectation by government that a commitment of taxpayer funds serves the public good. As we noted earlier, we urge that decisions on continued public funding of SSP consider the relative return on taxpayer investment compared with other energy technologies in particular, and other public sector investments in general. Also, past projections of large market penetration of new power-generation technologies (such as nuclear and solar power) have not been borne out by experience.[27] With regard to low-interest loans and loan repayment guarantees, they, too, await an industry commitment to a more advanced stage of development.

For several reasons, it seems reasonable to invite industry (especially electric utilities) to be involved in the technical and economic analyses that assess the commercial viability of SSP and the mix of R&D that might be appropriate to spur development of technologies intended for the commercial SSP market. One reason for this view is that trends toward electricity deregulation in the United States and abroad favor the private sector as the ultimate manager and operator of SSP systems. In addition, utility and energy companies can provide important insights regarding the technical and financial interface of SSP with terrestrial power systems. These companies also will be interested in the development of technical components that serve both space and terrestrial power needs (for instance, solar cells and power transmission).

This terrestrially based use of SSP aside, important applications of SSP may include provision of power to nonterrestrial systems such as the International Space Station, other large orbiting platforms, lunar bases, or deep space probes. In addition, space-based commercial markets might include SSP as a “power plug in space” for communications and remote sensing satellites. These opportunities should be investigated in the course of future analyses of SSP. Importantly, such discussion should include interested commercial entities.

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[27] In fairness, we should note that public R&D support did contribute to driving down the cost of solar and other renewable energy sources. However, their market penetration was impeded by the decline in conventional energy costs (see Burtraw and others 1999).

Box 6. Government Approaches to Influencing Private-Sector Investment: A Taxonomy

Cooperative arrangements	*Loans*
Research, development, and demonstration	Guaranteed
Anchor tenancy	Low interest (subsidized)
Risk indemnification	
Debt/equity participation	*Other*
	Standards and regulations
	Technology transfer and information dissemination
Tax Policies	
Tax holiday	
Tax credits	

V. Conclusions and Recommendations

Understanding the electricity markets in developed and developing countries in 2020 or so rests on informed judgment. We have sought to bring the best data sources and collective insights to bear in our study and hope that the framework we sketch serves useful as technological development of SSP proceeds.

We summarize our conclusions in three sets of observations and one list of recommendations for further study.

The Market for Electricity

Our first set of observations concerns the market for electricity in general, because it is the economic backdrop against which SSP would play a role as 2020 approaches:

- Current trends indicate increasing global demand for energy in general, and electricity in particular, from now to 2020. Electricity demand growth rates will vary significantly by region of the world and by stage of economic development. The highest growth rates will be in developing economies.
- Deregulation of electricity internationally will strengthen the trend toward decentralized, private ownership and management of utilities in most countries (developed and developing)—a major departure from the tradition of nationalized utilities.
- Nevertheless, investment in and operation of conventional electricity markets in developing economies likely will be, or will be perceived as, risky due to capital constraints, infrastructure limitations, and institutional and environmental factors.
- Constant-dollar electricity generation costs in 2020 likely will be no higher than prevailing recent levels and very likely will be significantly lower.
- The monetary value of environmental externalities in electricity generation appears to be significantly lower than some studies have indicated.

- Global climate change is not presently a major factor in power investment decisions in developing countries. Willingness to pay for "clean" technologies tends to rise with increasing incomes, but in developing countries, clean energy may not be the highest ranking priority among health and environmental concerns.
- Resource constraints on fossil fuels are unlikely to be a factor in this time frame, other than possible short-term supply disruptions caused by political and economic factors.

Taken together, these observations suggest that conventional electricity generation in both developed and developing countries may be more than adequate in terms of cost, supply, and environmental factors.

Challenges for SSP in Competing with Terrestrial Electricity Generation

Our second set of observations pertains specifically to the challenges that SSP is likely to face in this market:

- The relative immaturity of the technologies required for SSP makes it difficult to assess the validity of estimated costs and likely competitiveness of SSP. As in many space development initiatives, orders-of-magnitude reduction in the costs of space launch and deployment and other key technologies is critical. As these reductions occur, the economic viability of SSP may be more promising. Until then, it is premature for the U.S. government to make commitments such as loan guarantees or tax incentives for SSP.
- State-of-the-art conventional power-generation technologies increasingly incorporate numerous environmental controls, eroding somewhat the environmental advantage of alternatives to fossil fuel technologies.
- Actual and/or perceived health risks associated with exposure to electric and magnetic fields generated by SSP are likely to be of significant public concern.
- National security and national economic considerations may discourage some countries from participating in an SSP system operated by another country or group of countries. Countries with these concerns may require equity participation in SSP, limit their reliance on SSP only to a small share of their energy portfolio, or decline use of the technology altogether.

These findings argue for the merits of furthering technical advance in technologies required not only for SSP but for other space activities, and for special consideration of health and national security concerns that might be associated with SSP.

The Role of Economic and Market Analysis as Technical Considerations of SSP Progress

In the course of our study, the regular exchanges of information with the technical teams pursuing the engineering design of SSP proved invaluable to us and, we hope, useful to them. Economic and technical study must proceed in tandem, we believe, and specific recommendations as to further directions that economic study might take with this exchange in mind include the following:

- The energy industry should be invited to be "at the table" in relevant technical and economic analyses of SSP—that is, to both participate in conducting the analysis and learn about the results. The electric utility industry may be particularly interested in helping to guide development of SSP technical components that also can be applied in other terrestrial commercial power markets (for example, solar cells).
- Modeling of the economics of SSP should explicitly incorporate analyses of risk and uncertainty, include marketplace data about competition from terrestrial energy markets, and provide a means for structuring an efficient long-term technology development program that includes industry participation.
- Continued public funding of SSP for terrestrial power markets must consider the relative return on taxpayer investment in SSP compared with other technologies in general and energy technologies in particular (for example, photovoltaics). It should be noted that some past projections of large market penetration of new power-generation technologies (for example, nuclear and solar) have not been borne out by experience.

Issues that Warrant Additional Study

Finally, we have identified specific topics for future research in addition to continued economic study:

- Our focus in this report is on the use of SSP in terrestrial markets. SSP capabilities may be applicable to nonterrestrial systems such as the International Space Station, other large orbiting platforms, lunar bases, and other activities that are used to explore and develop space. The benefits and costs of these opportunities should be investigated in the course of future SSP analyses.
- Real and perceived safety, health, and environmental risks associated with SSP in its terrestrial and nonterrestrial power markets should be assessed and discussed in public forums that engage both scientists and the public.

Our final comment in concluding our study is that we seek neither to advocate nor to discourage further investment in SSP. Rather, our aim is to provide a considered framework with "placeholders" for new information as 2020 approaches and as such investment in SSP may continue. The challenges remain: to provide information that adds to and strengthens this framework, and to continue dispassionate dialog among economists and technical experts.

Appendix

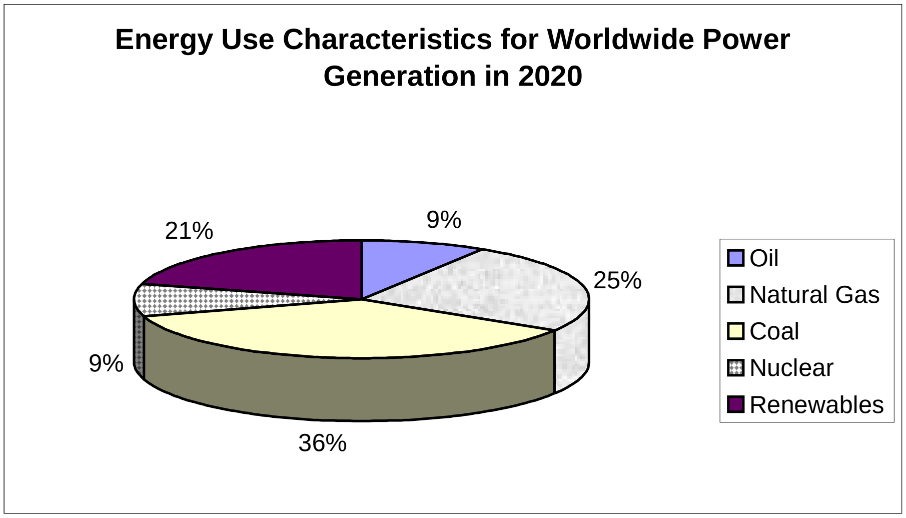
In this Appendix, we offer additional details to characterize future markets for power-generation technologies capable of providing baseload power in the 2015–20 reference time period. We use this characterization to help understand the technologies that may compete with satellite solar power (SSP).

First, we surveyed the literature on patterns of energy use; second, we made several technical assumptions; and third, we identified the financial and technical parameters of energy technologies that are likely competitors with SSP in the reference time period.

Energy Use Characteristics

According to the Energy Information Administration (EIA), if business proceeds as usual, then energy use patterns are not expected to change dramatically in the next twenty or so years. The chart below shows expected percentages of energy characteristics in 2020.[28] Fossil fuels will continue to supply up to 70% of the energy supply for power generation. By 2020, nuclear energy will decline to less than 9%, and renewable energy will constitute 21% of total power generation.

Figure A-1.



Technical Assumptions

We assumed that the power-generation technologies considered in this analysis must exist today and be commercially available in the reference time period. This assumption is based on the typical time lag from invention to commercialization for new technologies. History shows that it is very unlikely

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[28] EIA 1998b.

that a new technology can be conceived, prototyped, put into production, and claim a significant market share in a couple of decades.

Technologies Surveyed

We selected what we labeled as "evolutionary" and "innovative" technologies. Evolutionary technologies include natural gas combined cycle (NGCC), pulverized coal, coal integrated gasification combined cycle (IGCC), geothermal, and advanced nuclear power.

We define as evolutionary technologies those improvements over power industry systems currently in use and with well-known technical characteristics; documented performance histories; and large, installed infrastructures. They are all baseload power producers, have high reliability and availability, operate on a partial load, and can provide standby power.

Innovative technologies include photovoltaics, wind power, and fuel cells. They represent a break with the past and are not in widespread use today but could represent a sizeable component of the worldwide power generating system in the next century. They also tend to operate at much smaller scales than conventional systems, offering advantages in countries and locations with limited infrastructure.[29]

Evolutionary Technologies

Natural Gas Combined Cycle

NGCC plants are currently the second most prevalent form of electrical power generation. Major technological advances in recent years, along with natural gas prices, have made NGCC the current "technology of choice" for new generation. These plants are popular because they are inexpensive to build and operate, highly efficient, and available; they also emit lower levels of pollutants than coal plants. They are also highly modular and scalable, which makes them relatively easy to install as local requirements for power increase. NGCCs can range in size from 30 MW to more than 200 MW per turbine. Commercial plants can be constructed at an approximate capital cost of $320–$800/kW.

Pulverized Coal

Pulverized coal plants are the primary source of baseload power in the world today and are expected to be the second most prevalent source of power generation by 2020. They are usually very large (300 MW or more) because the greater capital costs associated with handling and burning the bulky solid fuel and its products lend greater weight to economies of scale. These plants are a very mature technology, expected to improve only slightly in the coming years. They are efficient and, except for CO_2 emissions, relatively nonpolluting when operated with advanced pollution control systems. They

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[29] These data were screened by the authors and show our estimation of trends in the reference time period. The raw data were compiled from multiple sources and validated by members of the team who represented Texaco, Inc., Energy Ventures Analysis, Inc., and Strategic Insight, Ltd.

also can take advantage of inexpensive indigenous coal deposits in many parts of the world, primarily in China. Commercial plants can be constructed at an approximate capital cost of $950–$1195/kW.

Coal IGCC

Coal IGCC power production uses the same combined cycle technology as in natural gas plants, with the addition of a coal gasifier. That additional stage, of course, means greater CO_2 emissions than a conventional coal plant. The gasifier converts coal gas into a clean fuel gas, which helps lower the emissions usually inherent in coal. It is projected that in 2020, the total world coal consumption will be 8,627 million metric tons per year. By some estimates, coal gasification could attain 30% of the coal-fired market by 2020.

Gasification can play a significant role in the competitive power generation marketplace. In markets where the demand for power is not supported by inexpensive indigenous fuels or where it is desirable to use various low value and/or waste feed stocks in combination with coal, gasification can be commercially competitive with other power generation solutions. Gasification also can handle feed stocks such as petroleum coke, municipal wastes, industrial and hazardous wastes, and biomass.

This technology also is well suited to situations that require multiple products, including fuel or town gas, hydrogen, chemicals, steam, and power. In addition, integrating the gasification facility with existing oil or chemical plants, power plants, and other industrial sites allows increased efficiency and flexibility. Commercial plants can be constructed for an approximate capital cost in the range of $800–$1,000/kW.

Geothermal

Geothermal energy taps the heat energy being continuously generated within the Earth and transmitted to the surface. To be useful for generating electricity or other geothermal applications, subsurface water must be present to provide a heat transfer medium. Current technology does not provide a way to tap the energy content of hot, dry rock.

Geothermal reservoirs are located and accessed using similar techniques to those used in oil and gas exploration and production. Once a suitable reservoir is identified, wells are drilled to bring the hot, high-pressure water to the surface. Reservoirs with water temperatures below 300 °F typically are used for space heating, and agricultural and industrial applications. Higher-temperature resources are more appropriate for electric power generation because they can generate steam to drive turbines. Although some geothermal reservoirs contain potential pollutants, such as sulfur compounds and greenhouse gases, net emissions are normally much lower than from fossil fuel combustion.

Current geothermal capacity is approximately 8,000 MW, generated in about twenty countries. An additional 12,000 MW equivalent of direct, nonelectric geothermal energy is being used for space heating and other purposes. Although the potential for application of geothermal energy to power generation is substantial, geothermal reservoirs of sufficient size and temperature for sustained production of electricity are localized and often not conveniently located. Future development could add an additional 10,000–15,000 MW in the United States and 50,000–100,000 MW worldwide.

Advanced Nuclear

Advanced nuclear power plants are being deployed in Japan, France, Russia, China, India, and many other countries. As a group, these new plants are designed to higher safety standards than previous generation systems. But even with these improvements, nuclear energy suffers from the public perception that the plants are inherently unsafe. Additionally, the problem of long-term storage of nuclear waste has not been resolved. Nuclear capacity is currently growing in niches around the world where national concerns over security of energy supplies outweigh the perceived risks. China, Japan, India, and other countries are expected to add a net 48,000 MW of nuclear generating capacity. In these countries, the economies of plant development are aided by quick construction times of three to four years, in contrast to the twelve to fourteen years required for the last few nuclear power plants built in the United States.

Innovative Technologies

Terrestrial Photovoltaics (PVs)

The price of photovoltaics has decreased substantially over the past two decades and is likely to be competitive with conventional power sources for peak power and as a baseload power supplier well before the reference period for our study. Cost per installed kilowatt is expected to be around $2,600 by 2020, compared with $3,200/kW installed in 1998.

These price decreases have widened the market for photovoltaics, leading to broad appeal in supplementing the conventional power grid as either peaking capacity or baseload power. However, using photovoltaics to supply baseload power requires an energy storage option, or backup power source, to provide power twenty-four hours a day. Energy storage systems add a level of complexity and cost that make it very difficult for terrestrial PVs to compete with other power-generation technologies. Potential storage options considered include batteries and superconducting magnetic energy storage (SMES).

Advanced zinc bromine batteries, expected to have a two- to five-hour storage capability, are expected to be available during the reference period. These systems would be modular and scalable. Expected capital costs for these batteries are $350/kW installed.

SMES operates by circulating direct current electricity in a superconducting magnetic coil. SMES systems have no emissions and a high ramp rate and dispatch efficiency. They can supply spinning reserve capacity and peak shaving capacity. In addition, large-scale systems are possible, and advanced systems are likely to be available during the reference period.

However, SMES systems also are expensive. Installed costs on the order of $700/kW (in 1992 dollars) for two hours of storage are expected to be typical of these systems in the reference time frame. SMES plants also incur siting limitations and operational issues caused by the high magnetic fields generated, which may limit where these systems can be used.

Wind Power

Wind power has made huge technical improvements and is already competitive with conventional power plants in areas with the requisite wind speed. Wind power systems are modular and can be constructed rather quickly.

Wind power systems suffer from the same limitation that plagues terrestrial photovoltaics in that when used as a baseload power system, an energy storage option or a backup source of power is necessary. As in the case of terrestrial photovoltaics, the cost of energy storage must be factored into the price of electricity. In addition, wind power also suffers from resource availability and accessibility of good wind power sites to transmission facilities. Expected costs of installation per kilowatt are expected to range between $670 and $1,235 during the reference period, without energy storage.

Fuel Cells

Fuel cells convert chemical energy directly into electricity without requiring combustion, producing very low emissions levels. They operate on hydrogen derived from natural gas, liquid fuels such as gasoline or methanol, or solids such as coal and biomass. Fuel cells are inherently modular, relatively compact for their power output, and highly efficient.

Currently, four major kinds of fuel cells are under development: proton exchange membrane, phosphoric acid, molten carbonate, and solid oxide. All will be available during the reference time period. If current trends hold, fuel cells will make major inroads into the power generation sector by the second quarter of the next century and capture a significant share of the transportation sector. The combination of modularity, easy installation, high efficiency, and very low emissions as well the ability to use gases from multiple sources should make the fuel cell part of any future power grid, while offering consumers the option of going off grid. Expected costs of installation per kilowatt are expected to range between $1,400 and $3,800 during the reference period.

Potential Future Ranges of Levelized Cost of Electricity

Table A-1 summarizes the range of our cost assessment of these technologies. The full table, with an explanation of assumptions, is available from the authors.

Table A-1. Authors' Cost Assessment of Available Technologies (Abbreviated).

	Estimated cost (cents/kWh)								
Levelized cost of energy	*Combined cycle gas turbine*	*Pulverized coal*	*Coal IGCC*	*Advanced nuclear*	*Wind*	*Wind with energy storage*	*PVs*	*PVs with energy storage*	*Fuel cells*
Low	1.7	3.1	3.0	3.0	2.6	3.2	5.9	9.1	3.9
High	5.5	7.2	10.2	6.0	10.0	16.6	54.5	41.9	17.4
Current	2.9	4.3	4.1	4.2	5.5	9.6	35.9	52.6	9.7

IGCC = Integrated gasification combined cycle; PVs = photovoltaics.

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