Electricity: Technology Development 5

Renewable energy technologies (RETs) have the potential to contribute significantly to electricity supplies in a cost-effective and environmentally sound manner. More than one-third of all U.S. energy goes to producing electricity, so the market for generating technologies is huge.[1] Bioenergy, geothermal, hydropower,[2] photovoltaic (PV), solar thermal, and wind RETs are discussed in this chapter. The cost of these technologies over time, their potential environmental impacts, and the nature and degree of their respective contributions will vary with the particular RET and its relative maturity, the locally available renewable energy resources, the specific application, and the effectiveness with which a variety of market challenges are met. Other technologies, such as ocean thermal energy conversion and solar ponds, appear to have less potential and have been dropped from federal research, development, and demonstration (RD&D) efforts; they are not discussed here.

This chapter examines four themes: 1) the status and role of RETs applicable in the electricity sector, and their associated industries, 2) the integration of these RETs into remote applications and electricity grids, 3) RD&D challenges that need to be overcome in order to commercialize these technologies, and 4) technical and policy issues associated with further development of

[1] The electricity sector share of U.S. energy consumption has increased from 25 percent in 1970 to 36 percent in 1990.

[2] Hydropower, of course, has long been a major low-cost contributor to U.S. and world electricity supplies. In 1992, hydropower provided 8.5 percent of U.S. electricity. See U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*, 1992, USDOE/EIA Report 0384(92) (Washington, DC: U.S. Government Printing Office, June 1993).

BOX 5-1: Fossil-Fueled Electricity: The Baseline

Fossil fuels currently power most electricity generation in the United States. Steam boilers, gas turbines, and diesel engines are the primary fossil-fueled technologies today New technologies becoming available Include fluidized bed systems for more efficiently and cleanly burning coal, gasification systems for gasifying coal as a fuel for gas turbines, various combinations of gas turbines and steam turbines in "combined cycles" so as to Improve overall system efficiency, and advanced gas turbine cycles such as the combined cycle or the intercooled steam-injected gas turbine Efficiencies of advanced cycles are expected to reach 60 percent and above within two decades. I

Costs of electricity from various fossil-fueled systems typically range from roughly 4¢ to 6¢/kWh for baseload systems and higher for load following and peaking power These costs depend strongly on the availability and price of fuel. Fossil-fueled systems have relatively low capital costs, high reliabilities, and a well-developed base of experience, this makes them formidable competitors to renewable energy technologies (RETs). Technical advances will allow fossil-fuel technologies to continue to be formidable competitors with RETs for some time to come.

[1] Douglas J Smith, "Advanced Gas Turbines Provide High Efficiency and Low Emissions *Power Engineenng,* March 1994, pp 23-27, and Paolo Chiesa et al , "Predicting the Ultimate Performance of Advanced Power Cycles Based on Very High Temperature Gas Turbine Engines, " paper presented at the American Society of Mechanical Engineers, Gas Turbine Congress, Cincinnati, OH, 1993

RETs for electricity generation. Chapter 6 complements this chapter by exploring many of the financial and institutional issues associated with RETs in electric power applications.

The cost of electricity generated by several of these RETs has dropped sharply over the past two decades with technological advances and modest commercialization efforts. For example, the cost of PV-generated electricity decreased by a factor of three and the cost of wind-generated electricity decreased by a factor of five between 1984 and 1994. Substantial field experience has been gained with several of these RETs as well. For example, some 8 GW of bioenergy, 2 GW of geothermal, 1.7 GW of wind, and 354 MW of solar thermal electricity-generating capacity were installed in the United States, and some 190 MW of PV capacity was installed globally between 1980 and 1990.

RETs such as biomass, geothermal, hydro, and wind can be cost-competitive with conventional energy technologies today (see box 5-1), depending on resource availability andlor cost. (Their use may be limited, however, by a variety of financial, tax, and institutional challenges, as described in chapter 6.) Other RETs, such as PVS and solar thermal, are generally more expensive and are currently limited to higher value applications, but have the potential to be widely competitive in the mid-term.

Electricity generation costs for several of these RETs are widely expected to continue to decline with further RD&D and as markets continue to develop and allow larger scale production and associated economies of scale and learning. This will make these technologies cost-effective in an increasingly wide range of applications even without considering their environmental benefhs. Cost, performance, and market advances for each of these technologies and their applications are discussed below.

RENEWABLE ENERGY TECHNOLOGIES AND INDUSTRIES

Renewable resources in the United States are very large, with one or more resources available almost everywhere. As discussed in chapter 1, site specificity, availability, and resource intensity need to be addressed in any particular application. The status and potential of these renewable energy resources and technologies,[3] and the industries that are developing and applying them, have changed significantly in the past two decades.

I Biomass

Biomass residues have long been burned by the forest products and other industries to generate process steam and electricity. As discussed in chapter 2, a growing awareness of the potential of dedicated bioenergy crops to improve the environment (including offsetting sulfur oxides (S OX) and greenhouse gas emissions (carbon dioxide) by fossil fuels), aid the rural economy, and reduce federal agricultural expenditures have prompted renewed interest in this resource. Biomass resources and technologies are described in box 5-2.

Roughly 8,000 MW of bioelectric[4] capacity is currently grid connected in the United States, compared with less than 200 MW in 1979. Additional bioelectric capacity is operated off-grids Steam turbines are now used. but a variety of new fuel handling and energy conversion technologies such as whole-tree burners and integrated gasification advanced gas turbine systems (including combined-cycle turbines and steam-injected gas turbines) promise to nearly double current efficiencies and substantially reduce costs (see box 5-2).

As biomass is "stored solar energy, " it can be used as needed to provide power in baseload or load following applications (see box 5-3). This makes biomass a very important complement to intermittent renewable such as wind and solar, which provide electricity only when the wind blows or the sun shines. Biomass can also be cofired with coal, a potentially important near-term application for reducing SO_x emissions, among other benefits, and thus may stimulate the market for biomass production. Of course, the relative value of biomass for electricity generation must be compared with its use for producing liquid or gaseous fuels (see chapter 4), for pulp and paper, or for other applications.

The bioelectricity industry[6] is among the most diverse among RETs. It includes forest products companies, such as Weyerhauser, which ha ve long cogenerated electricity at pulp and paper plants, as well as nonutility generators (NUGs) such as Wheelbrator and Thermo Electron. Equipment manufacturers include those that produce conveying equipment, boilers, electrical machinery, and controls. The industry also includes a number of biomass-specific equipment manufacturers such as Morbark Industries or Hallco Manufacturing. The transition to advanced gas turbines will include manufacturers such as General Electric and Pratt & Whitney. Engineering and construction

[3] RETs have been extensively reviewed elsewhere and so are only briefly examined here. RETs not examined here include ocean energy technologies (ocean thermal energy conversion, wave energy, tidal energy), additional bioenergy technologies (e.g., anaerobic digestion to produce methane, municipal solid wastes), fuel cells (chapter 4), energy storage technologies, and new transmission and distribution technologies. For further information, see World Energy Council, *Renewable Energy Resources: Opportunities and Constraints /990 -2(?20* (London, UK: World Energy Council, 1993); Thomas B. Johansson et al. (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993); U.S. Department of Energy, Office of Conservation and Renewable Energy, "Renewable Energy Technology Evolution Rationales, ''draft, Oct. 5, 1990; California Energy Commission, *Energy Technology Status Report* (Sacramento, CA: June 1990); John Doyle et al., *Summary of New Genera(ion Technologies and Resources* (San Ramon, CA: Pacific Gas and Electric Co., 1993); and American Solar Energy Society, *Progress in Solar Energy Technologies and Applications* (Boulder, CO: January 1994).

[4] Most of this capacity is based on burning wood from the forest products industry. Roughly 2,000 MW of municipal solid waste electricity-generating capacity is also included in this estimate. Agricultural residues and landfill gas account, very roughly, for about 500 MW of capacity.

[5] American Solar Energy Society, op. cit., footnote 3, p. 36.

[6] For a more complete listing of companies active in developing bioenergy equipment and powerplants, see "The 1995 International Competitive Power Industry Directory," *Independent Energy*, December 1994; and Susan Williams and Kevin Porter, *Power Plays: Profiles of America's independent Renewable Electricity Developers* (Washington, DC: Investor Responsibility Research Center, 1989).

BOX 5-2: Biomass Energy Resources and Technologies[1]

Biofuels—primarily from forest, agricultural, or municipal solid waste residues—currently provide about 3 EJ (2.9 Quads) or 3.5 percent of U.S. primary energy (see table 2-2 in chapter 2) These resources are now increasingly committed in some areas. For example, spot market prices for biomass in northern California have sometimes reached $250 to $3.75/GJ ($2,60 to $3 90/MMBtu) —as much as twice the normal cost, prompting the hauling of wood in from as far away as Idaho,[2] Consequently, interest in growing dedicated energy crops has developed (see chapter **2),**

The physical and chemical composition of biomass feedstocks varies widely, potentially requiring some tailoring of fuel handling and/or conversion technologies to specific biofuels, The relatively low bulk densities of biomass and large required collection areas limit the amount of biomass at any given site, with implications for the choice of generation technology, system efficiencies, and economies of scale.

Technologies

To generate electricity, biomass can be cofired with coal in conventional coal plants, separately burned in steam plants, or gasified to power gas turbines, fuel cells, or internal combustion engines, among others,[3] All of these uses of biomass are analogous to their fossil-fuel counterparts,

Virtually all biomass electric plants use steam turbines, which are generally small scale (typically 10 to 30 MW, with few over 50 MW) due to the limited amounts of biomass typically available at particular sites. Thus, they usually do not incorporate certain heat recovery equipment common to larger systems, and their efficiency tends to be low—l 7 to 23 percent in California, for example,[4] At larger scale sites, efficiency is higher. For example, the 50 MW plant in Burlington, Vermont, has an efficiency of 28 percent, In comparison, modern coal plants are much larger and typically run at 35 percent efficiency,[5] Very-large-scale biomass steam plants would likely have efficiencies roughly comparable to coal, but these scales may be limited by the large collection areas required and the corresponding problems of land availability and transport cost,

Steam turbine technology is fairly mature and few advances are foreseen for biomass improvements are possible, however, in biomass handling Whole-tree burners, for example, are under development and may reduce the required handling, increase net energy efficiencies silghtly, and avoid the cost of chipping the wood before burning It This might save about one-third of the cost of harvesting and delivering the biomass to the powerplant.[6]

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[1] Bioenergy resources, technologies, and environmental impacts are discussed at greater length in Thomas B Johansson et al (eds), Renewable *Energy* Sources *for Fuels and Electricity* (Washington, DC Island Press, 1993), U S Department of Energy, "Electricity from Biomass National Biomass Power Program Five-Year Plan (FY 1994-FY 1998), " draft, April 1993, Blair G Swezey et al , *The Potential Impact of Externalities Considerations on the Market for Biomass Power Technologies,* NREL/TP-462-5789 (Golden CO National Renewable Energy Laboratory, February 1994), and Antares Group, Inc "Electricity from Biomass An Environmental Assessment and Strategy, " draft, January 1993

[2] George A Hay III et al *Summary of New Generation Technologies and Resources* (San Ramon, CA Pacific Gas and Electric Co , Jan 8, 1993)

[3] Biomass can also be converted to ethanol, methanol, hydrogen, or pyrolysis oils, among others or burned for Space heat in the residential/commercial sector or for process heat in Industry

[4] Jane Turnbull, Electric Power Research Institute, personal communication, August 1993 In comparison Williams and Larson estimate these efficiencies at 14 to 18 percent See Robert H Williams and Eric D Larson "Advanced Gasification-Based Biomass Power Generation, " in Johansson et al (eds), op cit , footnote 1

[5] See, e g Electric power Research Institute, *TAG TM Technical Assessment Guide Electricity Supply—1989* EPRI P-6587-L, vol 1, Rev 6 (Palo Alto, CA September 1989)

[6] Leslie Lamarre "Electricity from Whole Trees, " *EPRI Journal,* January/February 1994, pp 16-24 and Stephen A Johnston et al , *Who/e Tree Energy Design,* Report TR-101564, 2 vols (Palo Alto, CA Electric Power Research Institute December 1993

BOX 5-2 (cont'd.): Biomass Energy Resources and Technologies[1]

A potentially higher efficiency and more economic alternative to the steam turbine is to gasify the biomass and then use the gas generated to fuel a high-efficiency gas turbine system. Gasification/ gas turbine technologies are now being developed, primarily for coal. Biomass gasifies at lower temperatures and more quickly than coal, reducing relative gasification costs After the biomass is gasified, the gas products are cleaned of particulate and other contaminants before being burned in a steam-injected gas turbine, a combined cycle, or other configuration.[7] There appears to be a basic understanding of the means for adequately cleaning gases for gas turbine applications with either fluidized bed gasifiers[8] or updraft gasifiers, although there has been no commercial demonstration of, in particular, alkali removal

Relatively small (5 to 100 MW_e) biomass gasifier/gas turbine systems are expected to have much higher efficiencies and lower unit capital costs (dollars per kilowatt hour) than steam turbine systems.[9] The upper end of this range is probably near the practical upper limit on the size of a biomass Installation due to the cost of transporting large quantities of biomass long distances.

Some have also proposed to use fuel cells with biomass gasification systems in the longer term. The relatively small scale of fuel cells might allow such systems to be located on a single farm, reducing some of the transport and handling costs and benefiting farm income. '" There remain, however, significant technical, logistical, managerial, and other challenges in realizing such systems

Biomass systems are now cost-competitive in many areas where a low-cost waste feedstock is available. Higher cost dedicated energy crops used with these higher efficiency systems are projected to be cost-competitwe in the future across a wide range of conditions. The cost of biomass-generated electricity is expected to be in the range of roughly 5¢ to 7.5¢/kWh in the year 2000 with the introduction of advanced gasification-gas turbines or other high-performance systems. ' Costs Will thereafter decline modestly with Incremental improvements in crops and equipment. The Electric Power Research Institute recently estimated that biomass-generated electricity could cost as little as **4.6¢/kWh** in the near term using whole tree burners [12]

Environmental Impact

Burning or gasifying biomass in a powerplant generates much less sulfur oxides (SO_x) than coal, but—as with any combustion process—does produce nitrogen oxides (NOx), depending on the combustion chamber temperatures It also generates particulate, volatile organic compounds, and various toxics. Criteria pollutants such as carbon monoxide, NO_x, SO_x, and particulate are reasonably well understood, and emissions should meet air quality standards. [13]

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[7] Hot gas cleanup avoids cost and efficiency penaloyords, and pressurization gasification avoids energy losses associated with compressing the fuel gas after gasification It is necessary, however, to remove trace amounts of alkali vapor from the gas before It enters the gas turbine

[8] E Kurkela et al , "Removal of Particulates, Alkali, and Trace Metals from Pressurized Fluid-Bed Biomass Gasification Products—Gas Cleanup for Gas Turbine Applications," *Biomass and Wastes XV* Donald L Klass (ed) (Chicago, IL Institute of Gas Technology, 1 991)

[9] This also holds true even for much larger steam systems

10 See, e g Royal Resources Corp "Electro-Farming, " Jan 1, 1994

11 U S Department of Energy, "Renewable Energy Technology Evolution Rationales, " draft, October 1990

12 "NARUC Hails Low-Cost Potential of Electricity from Biomass, PV," *Solar Letter,* Jan 6, 1995, p 3

13 Antares Group, Inc Op cit footnote 1

BOX 5-3: Utility Operat

There are significant daily, weekly, seasonal, and annual variations in power demand that a utility must meet. The utility operates a range of different equipment so as to meet this variable demand in the most cost-effective manner possible. This equipment is conventionally divided into three categories baseload, Intermediate (or load following), and peaking. Operation of this equipment is determined In part by equipment costs and efficiencies, operating hours and part-load operation performance, fuel costs, and ramp times (i.e., the time required to warm up the equipment for operation or to cool It down between operational times). Potential equipment failure or other problems are met by reserve capacity.

Baseload. Baseload plants are used to meet the largely nonvarying round-the-clock load [1] These are typically large (hundreds of MWs), relatively high capital cost ($1,500/kW) plants that use low-cost coal or nuclear fuels, Their high capital cost[2] is in large part a consequence of being designed to use low-cost fuels, Because they are operated for much of the year, their high fixed costs can be spread over many hours of operation,

Intermediate or /oad fo//owhg. As the name implies, intermediate plants fall between baseload and peaking plants in terms of the amount of time they are operated, their capital cost, and their fuel cost, They are operated to meet much of the normal daily variation in power demand

Peaking. Peaking plants are run for short periods of time In order to meet utlllty peak loads, such as summer air conditioning peaks or winter heating peaks. As these plants are operated for short periods over the year, there are few hours of operation to spread the fixed capital costs over. Consequently, much effort is made to minimize their capital cost. Low capital cost equipment requires premium fuels such as natural gas and so fuel costs for these plants tend to be high, Utilities have Invested substantial time and effort in limiting peak loads due to the expense of generating this power.

[1] Although there will likely be some variation in output depending on the use of other generation units

[2] Note that 'high" Capital cost here is in the context of conventional powerplants RETs may have a similar or higher capital cost, but lower fuel costs

firms that develop these powerplants include Babcock & Wilcox and Foster Wheeler. By one estimate, some 40 to 50 companies were involved in or investigating developing bioenergy projects in the mid- to late 1980s; that number has decreased to perhaps 20 or fewer with recent consolidations,[7] increased competition from natural gas, tightening bioenergy supplies in some areas, and other factors.

Significant expansion of bioenergy use for electricity will require the development of dedicated feedstock supply systems, perhaps through cooperative agreements between agricultural interests and biomass powerplants (see chapter 2). The long lead time and logistics of growing such feedstocks is likely to be a more significant constraint on the development of the bioenergy industry than manufacturing the equipment and building the powerplant systems.

Research, Development, and Demonstration Needs

RD&D needs include further developing: high-productivity crop varieties (chapter 2); equipment for feedstock harvesting, transport, and handling

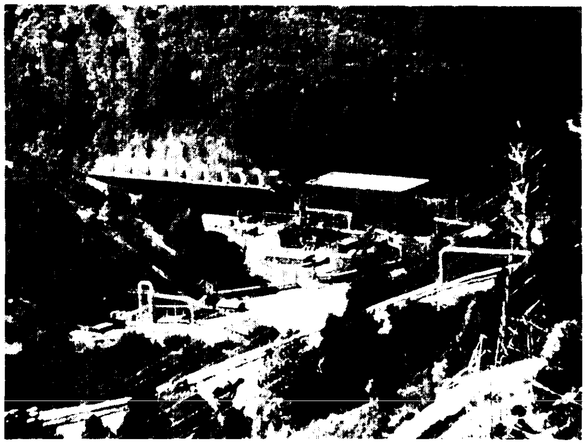
[7] Jan Hamrin and Nancy Rader, *Investing in the Future: A Regulator's Guide to Renewables* (Washington. DC: National Association of Regulatory Utility Commissioners, February 1993).

(chapter 2): feedstock drying; gasification and hot gas cleanup technologies (one of the most important and challenging needs); slagging controls; complete biomass gasification advanced gas turbine systems; whole tree burner or other minimal fuel preparation technologies; pyrolysis systems; and biomass fuel cell systems. Some of these technologies are ready for scale up and demonstration in pilot plants.

Successful development of these technologies—for example, improved crops, harvesting, transport, and biomass gasification advanced gas turbine systems-could lead to a viable industry with considerable benefits for rural communities. Further, if 50 GW of biomass electricity -generating capacity were realized by 2020,[8] savings, for example, of 1¢/kWh by these RD&D investments would correspond to $3 billion (1995 constant dollars) of annual savings in 2020.[9] Discounted to the present at a government rate of 5-percent real, the savings over the 30-year lives of these powerplants would have a present value of more than $14 billion.[10] There would be additional potential benefits to rural communities and to the environment (chapter 2). These savings are roughly 500 times the current annual federal investment in bioelectric RD&D. Although this hypothetical calculation is quite crude, it does suggest the potentially very significant leverage these RD&D investments could have.

| Geothermal

Geothermal electricity-generation systems extract heat from the ground to drive turbines. Modern day use of geothermal energy began in 1913 with a 250-kW turbine in Italy, followed in 1923 by installation of a 250-kW turbine at The Geysers, California, and other units at locations ranging from Iceland to Zaire. Geothermal resources and technologies are described in box 5-4.



GEOTHERMAL RESOURCES ASSOCIATION

Powerplant No 18 at The Geysers geothermal field m northern Calffornla This plant consists of two 55-MW single-flash units.

Geothermal systems are typically operated as baseload power; substantial variation in output may damage the underground resources in some cases. Geothermal systems can potentially also be operated in hybrid configurations with natural gas to improve overall output and economics of both.[11] Direct use of geothermal energy for space heating is possible as well.

Some 170 geothermal powerstations in 21 countries with 5,726 MW of electricity y generation capacity are in operation.[13] The United States has the largest installed capacity with about 2,500

[8] This much could be achieved by 2010 according to Electric Power Research Institute, *Strategies for Achieving a Sustainable, Clean, and Cost-Effective Biomass Resource* (Palo Alto, CA: 1993). This level of deployment is unlikely undercurrent conditions. See chapter 2 for details.

[9] Assuming a 70-percent capacity factor, All costs are in 1992 dollars. Of course, higher cost bioelectric systems would probably not be made use of as widely as lower cost bioelectric systems.

[10] At a market rate of 10-percent real, this would have a present value of $3 billion, or 100 times the current annual rate of investment.

[11] Electric power Research Institute, *Natural Gas Hybrid Power Plants for Geothermal and Biomass Resources, EpRI Rp 1671-07* (Palo Alto, CA: December 1992).

[12] Johansson et al (eds.) op cit., footnote 3; and U.S. Genera] Accounting office, *Geothermal Energy*, GAO RCED-94-84 (Washington, DC. June 1994).

[13] Lynn McLarty, Dyncorp., persona] communication, June 13, 1995.

BOX 5-4: Geothermal Energy Resources and Technologies[1]

Geothermal energy IS heat energy inside the Earth—either remaming from the original formation of the Earth or generated by the decay of radioactive isotopes inside the Earth. Only in particularly active areas, such as in volcanic zones or along tectonic plates, IS geothermal energy sufficiently concentrated and near the surface that it can be used economically,

Geothermal energy comes in four forms 1) hydrothermal fluids, 2) geopressured brines, 3) hot dry rocks, and 4) magma. Hydrothermal fluids—the only commercial geothermal resource—are hot water or steam in porous or fractured rock at depths of up to 4.5 km, and with temperatures ranging from 90°C to 360°C (190°F to 680°F), figure 5-1 maps their location,

Geopressured brines are hot, salty waters containing dissolved methane that lie at depths of 3 to 6 km trapped under sediment layers at high pressures, with temperatures of 90°C to 200°C (1900F to 390°F), Proposed systems to tap geopressured brines are generally hybrid systems, using both the geothermal heat and burning the methane to generate power. Texas and Lousiana gulf coast areas hold the only major geopressured resources identified to date (figure 5-1). Difficulties in extracting this resource include scaling (depositing minerals on equipment), its relatively low temperature (150°C or 300°F in test wells), and disposal of the brine produced, An experimental 1 -MW hybrid geopressured system at Pleasant Bayou, Texas, has demonstrated the technical feasibility of using geopressured resources for power generation, but the technology IS not yet cost-effective.

Hot dry rock (HDR) resources are regions of exceptionally hot rock, above 150°C (3000 F), that have little or no water in them Geothermal temperature gradients mapped in figure 5-1 Indicate the areas with the greatest potential for generating electricity the higher the temperature gradient, the greater the potential, Hot dry rock IS a very large potential resource, but needs further RD&D for it to become a cost-effechve and commercially viable technology,

Magma is molten rock with temperatures of roughly 700°C to 1,200°C (1 ,300°F to 2,200°F) and typically occurs at depths of 6 to 10 km Magma energy is the largest of all geothermal resources, but IS also the most difficult to extract—for example, exposing the drilling equipment to extremely hot conditions and the possible explosive release of hot pressurized gases, Cost-effective use of this resource appears unlikely for the forseeable future.

Although commonly termed a renewable resource, geothermal energy can be depleted if oversubscribed. At The Geysers in Northern California, for example, typical pressures have dropped from the initial level of 500 psi in 1960, at the start of development, to 200 psi by 19892 due to the more rapid removal of underground water and vapor resources than the rate at which they were being naturally replaced, One response in this particular case was to reinject water into the geothermal field. Whether this can bring the field back to full productity remains to be seen Extraction of heat may also decline for other reasons. For example, hot brines can leave mineral deposits (scale) on equipment or plug the pores of rocks as they are removed, impeding further flow

[1] For a more detailed discussion, see H Christopher H Armstead and Jefferson W Tester, *Heat Mining (New* York, NY E &F N Spon Publishers, 1983), M Economides and P Ungemach, *Applied Geothermics (New* York, NY John Wiley & Sons), Thomas B Johansson et al (eds), *Renewable Energy Sources for Fuel and Electricity* (Washington, DC Island Press, 1993), L Y Bronicki et al World Energy Conference, "Geothermal Energy Status, Constraints and Opportunities " draft, April 1992, U S Department of Energy, Energy Information Administration, *Geothermal Energy in the Western United States and Hawaii Resources and Projected Electricity Generation Supplies*, *DOE/E IA-0544* (Washington, DC September 1991)

2 John E Mock, testimony at hearings before the California Energy Conservation, Resources, and Development Commission, Sept 21, 1989

BOX 5-4 (cont'd.): Geothermal Energy Resources and Technologies

Resource exploration and development requires identifying, characterizing, and tapping the resource through well driling These technologies are similar to, but often more demanding than, those used in 011 and gas well drilling Recent development of slim-hole drilling may substantially lower costs for exploration and characterization of the resource [3]

Technologies

Technologies for utilizing geothermal resources for electricity production[4] Include direct steam, single-flash, double-flash, and binary systems The simplest technology is the piping of hydrothermal steam directly from underground reservoirs to drive turbines According to the U S Geological Survey, high-quallty steam resources are found in the United States only at The Geysers, Yellowstone National Park,[5] and Mount Lassen [6] About 1,700 MW of capacity is based on direct steam and is located at The Geysers

Single-flash units are similar, except that they make use of the much larger and more widespread resource of underground hot water instead of steam When this hot water is pumped to the surface and the deep underground pressures are reduced, it partially ' flashes" into steam in a flash-tank The steam then drives the turbine

A double-flash system uses a second flash-tank that operates at pressures Intermediate between the pressure of the first flash-tank and air pressure Double-flash systems are typically 10 to 20 percent more efflcient than single-flash systems, but at the additional capital cost of the second flash-tank and related equipment A Iittle over 600 MW of capacity in the United States is based on single- or double-flash steam units

Binary systems pump hot water to the surface and then use a heat exchanger to transfer the heat to a working fluid This working fluid is vaporized by the heat and then drives the turbine the cooled geothermal water is returned underground via an injection well Binary systems can use lower temperature fluids than is economically possible with flash technologies Binary systems also have minimal atmospheric emissions and reduced scale and corrosion of critical parts Binary plants tend to be small (5 to 10 MW) and modular, and can often be quickly built and Installed Their primary disadvantages are higher capital cost and some efficiency loss due to the heat exchanger Direct flash and binary systems are becoming relativly mature technologically About 200 MW of capacity in the United States is based on binary systems

These technologies generally need either air or water cooling for efflcient operation, just as for coal or nuclear steam plants Water may be Iimited in some areas, using geothermal fluids for coollng—which are

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3 H J Olson Electric Power Research Institute, "Geothermal Reservoir Assessment Based on Slim Hole Drilling Volume 1 Analytical Method Volume 2 Application in Hawaii EPRI TR-103399 December 1993

4 Geothermal energy can of course be used for direct heat applications as well ranging from district heating systems to low-f emperature industrial process heat

5 There is considerable concern that development of geothermal energy in the vicinity of Yellowstone National Park could damage such natural wonders as Old Faithful This has led to several legislative initiatives to limit such development See e g "Old Faithful Protect Ion Act of 1991 hearing before the Senate Committee on Energy and Natural Resources Subcommittees on Public Lands National Parks and Forests and on Mineral Resources Development and Product{on Feb 25 1992, as well as subsequent debate

6 An additional dry steam resource is reportedly located near Cove Fort UT See Susan Williams and Kevin porter Power *Plays Profiles of America's Independent Renewable Electricity Developers* (Washington DC Investor Responsibility Research Center 1989) p 203

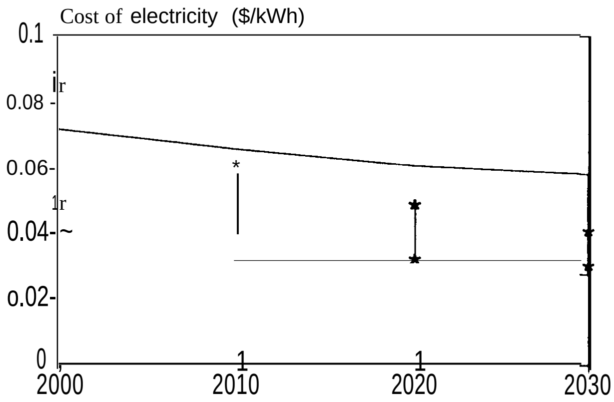
(continued)

BOX 5-4 (cont'd.): Geothermal Energy Resources and Technologies

then lost by evaporation—rather than reinfecting them into the ground may affect the geothermal resource.[7] This has been a factor in the decline of geothermal power output at The Geysers in California, Air cooling costs more and, in the summer, higher air temperatures reduce the powerplant generating capacity compared with the winter.

The cost of generating electricity from geothermal resources includes the cost of exploration for good resources, drilling wells, capital equipment, and operations and maintenance, usually including rejecting water Into the geothermal reservoir, Costs can be competitive today compared with coal where good-quallty hydrothermal resources are available.[8] Cost projections are shown in the figure; improved technologies—particularly for Identifying, characteriaing, and tapping geothermal resources—will expand the range of geothermal resources that can be tapped at these costs,

Cost Projections for Geothermal-Generated Electricity



NOTE The cost of geothermal energy is expected to be inthe range of about 4¢ to 7¢/kWh in the year 2000, declining moderately in following years, depending on the geothermal resource tapped and the technology used The shaded range encloses most of the expert estimates reviewed, with all estimates in constant 1992 dollars and, where necessary, capital cost and other estimates converted to ¢/kWh using discount rates of 10 and 15 percent (with 3 percent inflation) High and low values developed by the Department of Energy are shown as *

SOURCE Off Ice of Technology Assessment, based on U S Department of Energy, "Renewable Energy Technology Evolution Rationales, " draft, October 1990, and Science Applications International Corp., "Renewable Energy Technology Characterizations, " draft, March 1990

Environmental Impact

The environmental impact of geothermal power varies with the resource and the technology used. Direct steam and flash systems generally release gases to the atmosphere; methods have been developed to first remove pollutants such as hydrogen sulfide before these gases are released. Small quantities of brines may also be released, Binary systems generally reinject all gases and brines back into the reservoir so have few or no emissions. Overall sulfur and carbon dioxide emissions for geothermal plants are typically less than 4 percent of those by coal- or oil-fired powerplants.[9] Large quantities of cooling water may be needed in some cases, just as for fossil plants, Where geothermal resources occur in scenic areas, particular attention to siting and landscaping may be necessary if they are to be developed, Land requirements for geothermal units are generally quite small (see table 1-2 in chapter 1), but land may also be needed in some cases for disposal of waste salts from geothermal brines, There may also be some subsidence of land overlying wells.

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7 Condensate from flash steam plants can be used in a cooling tower to evaporate and provide cooling for the Power cycle This typically results in 80 percent of the geothermal fluid being lost and only 20 percent being available for reinjection in the reservoir Reinjection, however, must be done carefully in order to prevent excessive cooling of the reservoir and lowering the quality of the available geothermal resource See Gerald W Braun and H K "Pete" McCluer, "Geothermal Power Generation in United States, " *Proceedings* of *the IEEE,* VOl 81, No 3, March 1993, pp 434-448, see table 1

8 Ibid

9 Ibid

MW net[14] (up from about 500 MW in 1979) spread among some 70 plants in operation with contracted power costs as low as 4.6¢/kWh. As of 1993, about 1,700 MW of this net capacity was at The Geysers, California, and 800 MW of capacity was located elsewhere in California, Nevada, and Utah. In addition, some 300 MW of capacity was under construction or announced.[15]

The geothermal industry has changed considerably over the past 10 to 15 years. Several major oil companies and their affiliates were active in geothermal development in the early 1980s due to their expertise in underground resource exploration and development—the most difficult part of geothermal energy development; all but Unocal have now ended their geothermal activities,[16] and Unocal—the largest developer—has recently sold some of its geothermal properties. Most developers now are small- to medium-size firms such as California Energy,[18] Calpine, and Ormat.

Until the mid- 1980s, private companies generally developed the geothermal field and sold the steam/hot water to public utilities, which were the primary owners and operators of geothermal plants for power generation. Most recent geothermal projects have been built, owned, and operated by nonutility generators that developed both the geothermal field and the powerplant and sell the electricity to utilities. NUGs now account for more than one-quarter of total geothermal capacity.[19] Currently, fewer than 10 firms account for most of the activity in geothermal energy. Supporting firms include well drilling and geoscience companies and equipment suppliers.[20]

Geothermal development in the United States has slowed in recent years due to low growth in the demand for new generating capacity by many utilities in areas with good geothermal resources; difficulty in funding capital-intensive and risky geothermal development; and low natural gas and other fossil fuel prices. In addition, opportunities may, in some cases, be limited by subsidies for competing technologies. For example, the U.S. Department of Energy (DOE) plans to spend $135 million to help build and operate a 100 MW coal-fired powerplant in Nevada under the Clean Coal program, reducing the need for other new capacity.[21] As a result of slower U.S. growth, geothermal companies are becoming more active in overseas markets. California Energy, for example, is developing or negotiating projects in the Philippines, Indonesia, and elsewhere.[22]

Research, Development, and Demonstration Needs

Additional technology development could be useful in a number of areas, including: improving the

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14 Capacity of The Geysers has declined in recent years due to overdrawing of the underground water resources, leaving a net operating capacity of about 1,700 MW out of about 2,000 MW installed capacity.

15 Gerald W. Braun and H.K. "Pete" McCluer, "Geothermal Power Generation in the United States," Proceedings *of /he IEEE*, March 1993, pp. 434-448.

16 Some ~edium.size independent oil company affiliates, such as Freeport-McMoRan Resource Partners, continue to be involved in geothermal development.

17 For the sale of Unocal's geothermal leaseholds to Magma, see, e.g., Jeannie Mandelker, "Geothermal's Hot prospects," *Independent Energy*, November 1993, pp. 16-19.

18 California Energy Company took over Magma Power Company in December 1994 in part due to the need for greater operational resources to compete effectively in international markets. See Harriet King, "Magma Agrees to $950 Million Offer," New *York Times*, Dec. 6, 1994; and "Cal. Energy Hot for Magma But the Latter Is Resisting," *Electricity Journal*, November 1994, pp. 5-6.

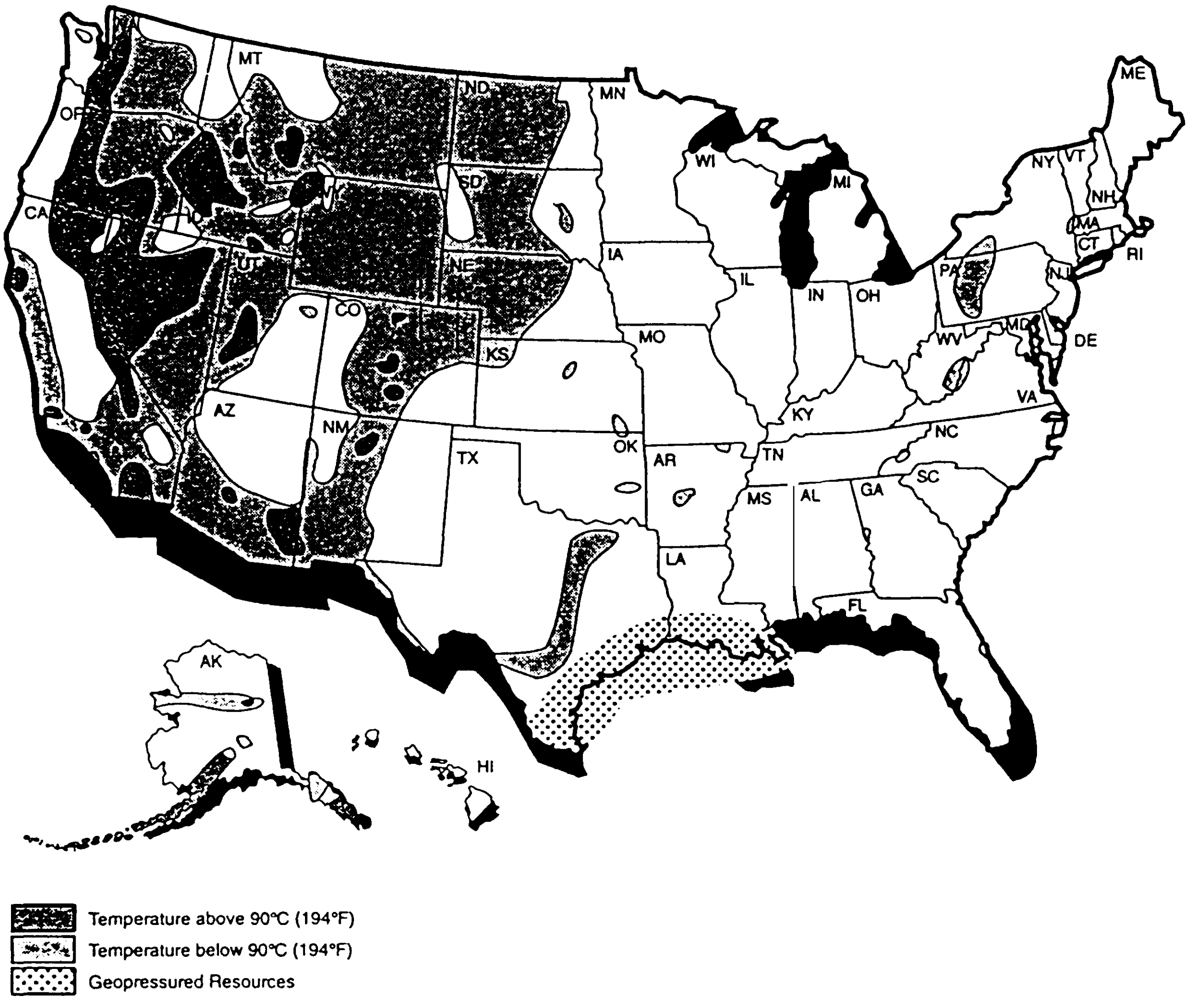
19 C) ffice of Conservation and Renewable Energy, op. cit., footnote 3.

20 Hamrin and Rader, op. cit., footnote 7.

21 U.S. General Accounting office, op. cit., footnote 12.

22 Mandelker, op. cit., footnote 17. See also footnote 18.

FIGURE 5-1A: Hydrothermal and Geopressured Geothermal Resources in the United States

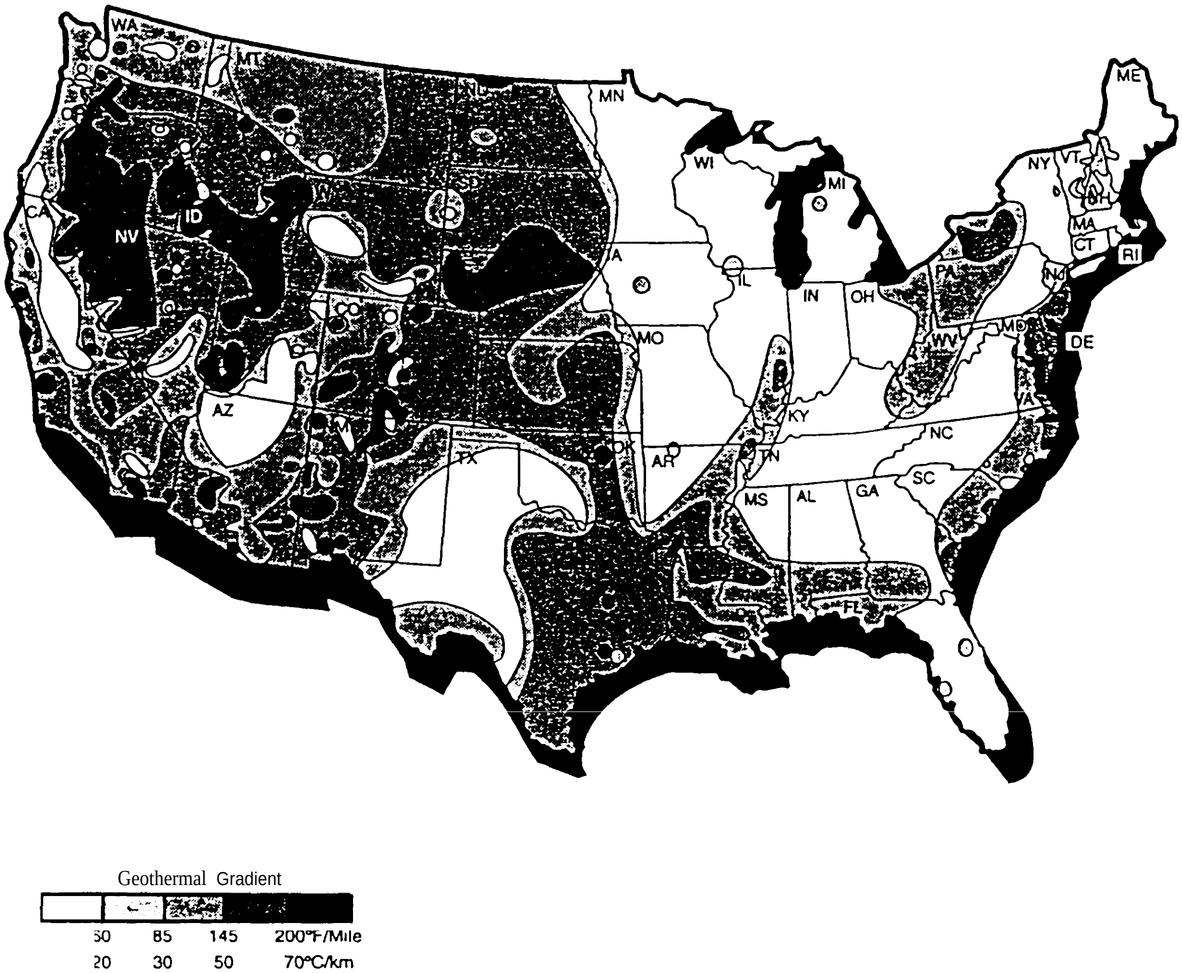


SOURCE U S Geological Survey, as cited in U S General Accounting Off Ice, *Geothermal Energy, GAO/RCED-94-84* (Washington, DC. June 1994)

ability to identify and characterize suitable geothermal fields; developing down-hole instrumentation and other equipment for geothermal characterization and real-time monitoring that can survive high temperatures and corrosive geothermal brines; improving well drilling—particularly for hard rock[23]—and related technologies; enhancing geothermal field permeability; reducing scale and corrosion of equipment by hot geothermal brines and improving materials for operating at high temperatures; improving the performance

[23]The rock overlaying geothermal resources is often harder and more abrasive, and the temperatures are higher, than that for oil and gas W'ells.

FIGURE 5-1B: Hot Dry Rock Geothermal Resources in the United States



SOURCE: U.S. Department of Energy, as cited in U.S. General Accounting Office, *Geothermal Energy*, GAO/RCED-94-84 (Washington, DC: June 1994).

of the various prime mover—single or double flash, binary, or others—technologies; and developing the capability to exploit geothermal hot dry rock and other resources.[24] Analysis of various types of hybrids, such as natural gas-geothermal hybrids, would be useful to identify opportunities where the efficiency and cost-effectiveness of both geothermal and fossil systems can both be improved simultaneously. The existing geothermal industry is too small to support a reasonable level of RD&D in these areas at this time and technologies, such as hard rock drilling for hot dry

24 See L.Y. Bronicki et al, World Energy Council, "Geothermal Energy: Status, Constraints, and Opportunities," draft, April 1992.

rock geothermal resources, are of relatively little interest to the well-capitalized oil and gas industries due to the different nature of the rock strata overlying oil and gas deposits.

I Hydroelectricity

Hydroelectric generation systems use the energy in flowing water to turn a turbine. As of 1988, the United States had about 88 **GW** of hydroelectric-generating capacity—64 GW of conventional large-scale hydro, 7 GW of small-scale hydro, and 17 GW of pumped storage—with net generation of about 8.5 percent[25] of total U.S. electricity supply. Globally, hydropower currently provides about 20 percent of world electricity supplies.[26] Hydropower resources and technologies are described in box 5-5.

The primary change for hydropower in recent years has been increasing concern over its potential impacts on, for example, aquatic habitat, the land it inundates, and recreation. In turn, these factors have increased the time required and cost of meeting regulatory requirements.

In its conventional form (with dam storage), hydropower can provide base, intermediate, or peaking power. Because it can be rapidly dispatched as needed, it can serve a particularly valuable role in backing up intermittent power from sources such as solar and wind.

Before the 1930s, most hydropower was developed by industry or utilities. During and following the Depression, a large share of U.S. hydroelectric power was developed through federal support, including the Tennessee Valley Authority and the Columbia Basin Project. By 1940, some 3,100 conventional hydro sites were in operation. A variety of factors cut the number of operating projects to just over 1,400 by 1980,[27] although net capacity continued to increase, roughly tripling between 1950 to 1975.[28] The two oil crises, enactment of several tax credits,[29] and regulatory changes—particularly the passage of the Public Utility Regulatory Policies Act—spurred independent development of hydropower during the 1980s. Independents have developed many more, but smaller, sites than utilities, while utilities have developed more MWS of capacity. More recently, environmental and regulatory concerns have strongly impacted hydropower relicensing as well as new licensing.

Hydropower developers generally include individuals and small partnerships for mini-hydro projects (up to 5 MW); independent development companies such as Consolidated Hydro, Independent Hydro Developers, Synergics, and others for small-hydro projects (5 to 50 MW); and utilities for medium (50 to 100 MW) or large (>100 MW) projects.[30] There has been relatively little development of hydropower by the federal government in recent years.[31] construction follows a similar pattem, ranging from small local construction firms for small projects, to firms such as Morrison

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25 U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*, DOE/EIA-0384(90) (Washington, DC: May 1991), table 90.

26 U.S. Congress, Office of Technology Assessment, *Energy in Developing Countries*, OTA-E-486 (Washington, DC: U.S. Government Printing Office, January 1991).

27 Nan Nalder, "Fixing Hydro—The Forgotten Renewable," *Electricity Journal*, April 1992, pp. 12-21.

28 Keith Lee Kozloff and Roger C. Dower, *A New Power Base: Renewable Energy Policies for the Nineties and Beyond* (Washington, DC: World Resources Institute, 1993).

29 These tax credits, including an energy tax credit under the Crude Oil Windfall Profits Tax Act, an investment tax credit, and accelerated depreciation, have been phased out.

30 The types of ownership and the size of projects indicated here are illustrative only. Ownership and project size may vary considerably from these values.

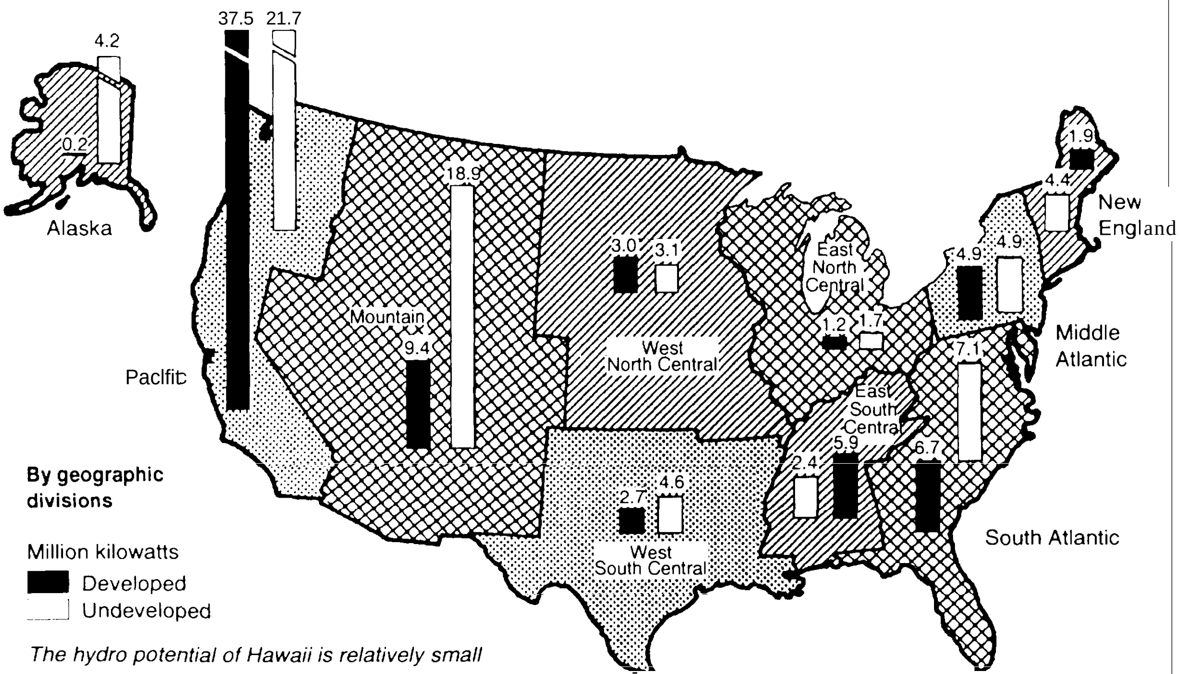
31 Among notable exceptions were five Bureau of Reclamation hydro facilities brought online in 1993. Maria J. Barnes and Laura Smith-Noggle, ". Hydropower '93: The Year in Review," *Hydro Review*, vol. 12, No. 8, 1994, pp. 12-20.

BOX 5-5: Hydropower Resources and Technologies

U S hydropower resources are fairly well developed. More power, however, could potentially be obtained from existing facilities, including capturing reservoir spill,[1] upgrading equipment, and Installing equipment at dams not now used for power [2]

By one estimate, a potential of about 76 GW of conventional hydro and 19 GW of pumped storage capacity were untapped in the United States as of 1988 (see figure),[3] The U.S. Department of Energy estimates that about 22 GW of this potential could be developed economically at current prices and 19 GW more could be developed with a price premium of 2¢/kWh. As much as 13 GW of the remainder might be developed with appropriate attention to environmental and safety Issues, further development of technolo-

U.S. Conventional Hydroelectric Generation Capacity, Developed and Undeveloped



The hydro potential of Hawaii is relatively small and thus is not shown.

SOURCE Federal Energy Regulatory Commission *Hydroelectric Power Resources of the United States, Developed and Undeveloped FERCO0070* (Washington DC January 1992) cited in U S Department of Energy Energy Information Administration "Renewable Resources in the U S Electricity Supply DOE/EIA 0561 February 1993

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[1] U S Army Corps of Engineers Institute for Water Resources "National Hydroelectric Power Resources Study Volume I " May 1983

[2] Marc Chupka and David Howarth *Renewable Electric Generation An Assessment of Air Pollution Prevention Potential,* EPA/400 *R-92 005* (Washington DC U S Environmental Protection Agency March 1992) citing the Federal Energy Regulatory Commission

3 Federal Energy Regulatory Commission Hydroelectric Power Resources of the United States " January 1988

(continued)

BOX 5-5 (cont'd.): Hydropower Resources and Technologies

gy, and the above price premium. In addition, there are an estimated 12,5 to 17.5 GW of run-of-river and other capacity, of which perhaps 10 GW could be tapped with further development of low-head technologles.[4]

Technology

Hydroelectric technologies—dams,[5] run-of-river,[6] and pumped storage[7]—are generally considered to be mature. Turbine efficiencies are typically in the 75 to 85 percent range. Nevertheless, there have been evolutionary technological developments in a variety of areas, These include better understanding of both soils and manmade materials in designing and constructing dams and related equipment, Improvements in dam constrution techniques and materials, use of devices such as inflatable weirs to raise upstream water levels, and electronic controls of turbine speed and electronic power conditioning.[8]

The capital costs for new U.S. hydropower facilities range widely around a median price of about $2,000/kW, operations and maintenance costs at large facilities typically average roughly 0.5¢/kWh, operating lifetimes are usually assumed to be 45 years, and operational capacity factors are 36 to 45 percent. Together, these parameters give costs of roughly 6¢/kWh Hydropower costs often range between 4.5¢/kWh to 7.5¢/kWh, with considerable varilation above and below this range. No significant cost reductions are forseen.[9] These costs are generally competitive with fossil-generated power.

Environmental Impact

Although hydro has long proven to be a reliable and cost-effective resource, and once constructed, does not release carbon dioxide,[10]" a number of environmental concerns have been raised. These include Inundating wildlife habitat; changing aquatic ecosystems and water quality—including temperature, dissolved oxygen and nitrogen, and sediment levels, causing high mortality among fish passing through the

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[4] Solar Energy Research Institute, "The Potential of Renewable Energy, An Interlaboratory White Paper, " March 1990

5 Most hydropower facilities use dams to raise the water level and thus Increase the potential energy, and to provide storage of water so as to smooth out seasonal fluctuations in the amount of water available for generating power

6 Run-of-river systems do not use a dam but may use other structures reducing, but not eliminating, associated costs and environmental Impacts Lack of dam storage Increases susceptibility to seasonal fluctuations in output

7 pumped storage systems are not a RET, but could be used to store power generated by RETs or to complement RET Power output Pumped storage systems use electricity (usually from a baseload powerplant—typically coal or nuclear powered) to pump water to an upper reservoir, this water is later dropped through a generator back to the lower reservoir to generate needed peak power Typical pumped storage systems are now 70 to 80 percent efficient over the entire cycle Limited suitable sites for pumped storage-near both cities and large electric generating plants—have led some to consider use of underground caverns for the lower reservoir See John Dowling, "Hydroelectricity," *The Energy Sourcebook A Guide to Technology, Resources, and Policy,* Ruth Howes and Anthony Fainberg (eds) (New York, NY American Institute of Physics 1991)

[8] Geoffrey P Sims, "Hydroelectric Energy, " Energy *Policy* October 1991, pp 776-786, and Eric M Wilson, "Small-Scale Hydroelectricity, " *Energy Policy,* October 1991, pp 787-791

9 Allan R Hoffman, "DOE's Approach to Renewable Energy in the Utility Sector, " presentation at the Workshop on Generation Of Electricity from Renewable Sources, American Physical Society, Washington, DC, Nov 6-7, 1992

10 Constructing hydro plants usually entails extensive earth moving using diesel-powered equipment and use of large amounts of concrete, both resulting in emissions of carbon dioxide In addition, the Inundation of large amounts of biomass by the dam may result in the emission of significant amounts of methane as the biomass decomposes See, e g John W M Rudd et al , "Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases?" *Amble,* VOI 22, No 4, June 1993, pp 246-248

BOX 5-5 (cont'd.): Hydropower Resources and Technologies

turbine and affecting fish migrations.[11] Large and/or rapid variations in hydropower output may also damage aquatic habitats, streambeds, or cause other problems.[12]

The history of federal, state, and court considerations in balancing the many competing interests in the hydro arena is long and complex.[13] In recent years, the Federal Energy Regulatory Commission has recently begun to revamp its hydropower licensing procedures to both better meet environmental concerns while reducing the burden on developers.[14]

[11] This is the focus of another OTA assessment, *Technologies To Protect Fish at Darns,* forthcoming The risk of a dam failure and the potential impact on people and towns downstream is also of primary concern, but is not addressed here

[12] Because of such longstanding environmental concerns, a large body of legislation has directed attention toward the environmental impacts of hydropower development including the Water Resources Planning Act Public Law 89-80, the Wild and Scenic Rivers Act, Public Law90-542, the National Environmental Policy Act, Public Law91 -190 the Clean Water Act, Public Law92-500 and the Endangered Species Act, Public Law96-205 In 1986, the Electric Consumers Protectlon Act of 1986 directed the Federal Energy Regulatory Commission to give equal consideration to environmental concerns in its hydro licensing procedures

[13] For a discussion see, e g George C O Connor, "Will the Commission's Hydropower Program Revive in the 90s?" Energy Law *Journal,* vol 14, No 1, 1993, pp 127-151, Amy Koch, "The Battle for One-Stop Shopping, " *Independent Energy,* February 1992 pp 38-40, George Lagassa "The Exemptlon Dilemma, " *Independent Energy,* July/August 1993. pp 52-56 and Nan Nalder, Fixing Hydro—The Forgotten Renewable " *Electricity Journal,* April 1992, pp 12-21

[14] "FERC Revamps Its Procedures for Hydro, " *Electricity Journal,* October 1993, pp 15-16

Knudsen, Dillingham, Ebasco, and Stone& Webster for larger projects. Financing likewise ranges from limited partnerships or small business loans for small projects to large institutional investors in big hydro projects. Producers of hydro turbines include Voith,[32] Kvaerner (Norway), Sulzer (Switzerland), Ossberger (Germany), American Hydro, STS Hydropower, and Hydro West.

There has been little new development of hydropower in the past four to five years. An important reason for the slowdown is the substantial and increasing front-end development cost and time for permitting and licensing. The long lead times for development—perhaps three years for permitting, three years for licensing, and two to three years for construction-do not well match shortening utility planning horizons in the increasingly competitive electricity market, particularly with low natural gas prices and short lead times for gas turbine installations. As a result, many hydro power companies are concentrating on opportunities for rehabilitating and upgrading plants. [33] Contributing to this effort has been the Federal Energy Regulatory Commission's Efficiency Upgrade Program, introduced in 1991, which streamlines the approval process for such changes.[34] Some, including both independents and utility subsidiaries, are also looking overseas for new opportunities.[35]

RD&D *Needs*

Although hydro technologies are relatively mature, considerable interest is developing in systems that reduce the impact on aquatic species and habitats. This includes turbines that safely pass

[32] Voith (Germany) purchased Allis Chalmers turbine business but continues to manufacture in York, Pennsylvania.

[33] George Lagassa, "Repowering Hydro," *Independent Energy,* October 1992, pp. 46-50.

[34] Edward Fulton, "Gaining Capacity Through FERC's Efficiency Upgrade program," *Hydro Review,* August 1994, pp. 36-42.

[35] George Lagassa, "Small Hydro Goes International," *Independent Energy,* November 1992, pp. 71-73.

fish and aerate the water. Other research and development (R&D) needs include variable speed and pitch turbine systems, improved wear-resistant materials, and better forecasting.[36]

Photovoltaics

Photovoltaics (photo for light, voltaics for battery), or solar cells, convert sunlight directly into electricity. Unlike wind turbines or solar thermal systems, PVS have no moving parts,[37] they use solid-state electronics instead. Solar resources are described in box 5-6 and applies to solar thermal as well as PV. PV technologies are described in box 5-7.

Over the past two decades, PV efficiencies and reliability have increased significantly, manufacturing capabilities have improved, and other system components have advanced. As a consequence, the cost of PV modules has decreased by nearly 10 times since the mid- 1970s. PVS are now cost-competitive in numerous market niches and their continuing drop in price is making them cost-competitive in an ever broadening range of applications. World production of PVs in 1993 was about 61 MW, more than double that in 1987.[38]

Because of the small scale and low-maintenance characteristics of many PVs,[39] they are widely used in remote applications such as communications relays or water pumping stations. Electric utilities are also beginning to consider PVs for numerous applications, and more than 60 classes of potentially cost-effective applications have been identified.[40] In grid applications, the extent to which PV power can offset other electricity-generating capacity depends on its match with the electricity load and potential complementary combinations with other generation resources such as wind.

PVs may also have a substantial role to play in building-integrated systems. This application is expected to reduce installed PV system costs by several means including:

1. The dual use of PV modules for power generation and as part of a building's roof or exterior walls will offset capital costs by displacing roofing or wall materials.
2. A separate support structure for the PV system will be unnecessary since the building itself will serve this function.
3. No additional land will be required for the PV array (this is a significant bonus in crowded urban areas and of particular interest to the Japanese).
4. Utilities may offer attractive rates for this demand-side management strategy according to its ability to reduce the need for additional central generating capacity.

The PV industry ranges from small entrepreneurial startups to subsidiaries of Fortune 500 giants. Following the oil crises, a number of large companies entered the PV industry, many of which subsequently exited due to falling fossil energy prices, long technology and market development times for PVs, and higher near-term returns from other investments. For example, Atlantic Richfield sold its Arco Solar subsidiary to Siemens (Germany) in 1989 and Mobil Oil Company[41] sold its Mobil Solar subsidiary to ASE GmbH (Germany) in July 1994. Other recent sales of U.S. PV firms to foreign companies are de-

36 For a more complete listing of possible areas for R&D, see North American Hydroelectric Research and Development Forum, *Repowering Hydro: The Renewable Energy Technology for the 21st Century* (Kansas City, MO: HCI Publications, September 1992).

37 If mounted on a tracking collector, however, there will be moving parts associated with the collector.

38 Paul D. Maycock, *International Photovoltaic Markets, Developments and Trends Forecast* 102010 (Casanova, VA: Photovoltaic Energy Systems, Inc., 1994).

39 And, of course, they do not need fuel transported to the site.

40 E.C Kern, Jr., *Early, Cost-Effective Applications of Photovoltaics in the Electric Utility Industry*, EPRI TR-100711 (Palo Alto, CA: Electric Power Research Institute, December 1992).

41 At press time, it was not known how substantial a holding Mobil retained in its former solar subsidiary.

scribed in chapter 7. Major firms that have withdrawn from PV manufacturing also include Boeing, Exxon, General Electric, Honeywell, Kodak, Martin Marietta, and Standard Oil of Ohio.[42] This has shifted the PV industry toward smaller firms,[43] although large firms such as Amoco (through its subsidiary Solarex) continue to be active.

In the past several years, a few larger firms have again expressed interest in PVs. For example, Coors (through Golden Photon) has entered PV development and manufacturing. Amoco/Solarex and Enron, the largest U.S. natural gas company, recently proposed a venture to build a 1OO-MW PV powerplant in Nevada with a cost of electricity at 5.5¢/kWh. This very low cost, years earlier than expected, may be possible due to the relatively large scale of production in this proposal, use of government land, federal renewable energy tax break, and financing with tax-free industrial development bonds.[44] Several other large firms are carefully examining potential partners or acquisitions.

Factors driving this new-found interest include substantial technological and manufacturing advances in PVs, the recognition that there are many higher value niches where PVs are already cost-competitive, a rapidly growing international market, and the expectation that environmental technologies will be increasingly important.

Some 19 firms currently manufacture PVs in the United States,[45] but Siemens (Germany) and Solarex alone account for about 80 percent of this production (see table 7-3). PV manufacturing equipment is produced by companies such as Spire, power conditioning equipment is produced by companies such as Omnion Power Engineering, and system integrators include Photocomm.[46]

Two overall strategic perspectives are influencing the direction of the PV industy. Many have long viewed utility bulk power markets as the goal and saw large-scale manufacturing to dramatically lower costs as the key to getting there. Scaling up manufacturing to that level, however, is a substantial challenge. The Electric Power Research Institute (EPRI), for example, has demonstrated in the field the technical potential of an integrated high-concentration PV technology—winner of a 1994 R&D 100 Award-built by AMONIX, Inc., and estimates that at a production scale of 100 MW/year, the cost of electricity from this system can be lowered to 8¢/kWh. EPRI believes that volume production is a key to further cost reduction.[47]

At this scale of production, comparable or lower costs are also expected for various thin film PVs such as CIS, CdTe, and a-Si as well as certain other PV technologies. However, 100 MW/year is almost twice the current world market, which is now spread among some 14 large (>1 MW/year) producers and a host of smaller producers (see table 7-3). Further, the long lead time to develop markets seriously restricts the possibility of building, for example, a 1OO-MW production plant and forcing prices down with volume production; most producers simply do not have the capital to absorb several years of product output at these scales while they develop a sufficiently large market for their output. So far, even PV firms with deep-pocketed parents have not been willing to

42 Williams and Porter, op. cit., footnote 6.

43 Ibid.

44 Allen R. Myersen, "Solar Power, for Earthly Prices," New *York Times, Nov.* 15, 1994, p. D].

45 "Total Solar Collector Shipments Dip as Imports Soar, Exports Climb: ElA," *The Solar Letter*, vol. 4, No. 18, Aug. 19, 1994, pp. 197-200.

46 For a listing of companies involved in photovoltaic manufacturing, system integration, and related activities, see, e.g., "Membership Directory," *Solar Industry Journal, vol. 5, No.* 1, *1994,* pp. *54-76.*

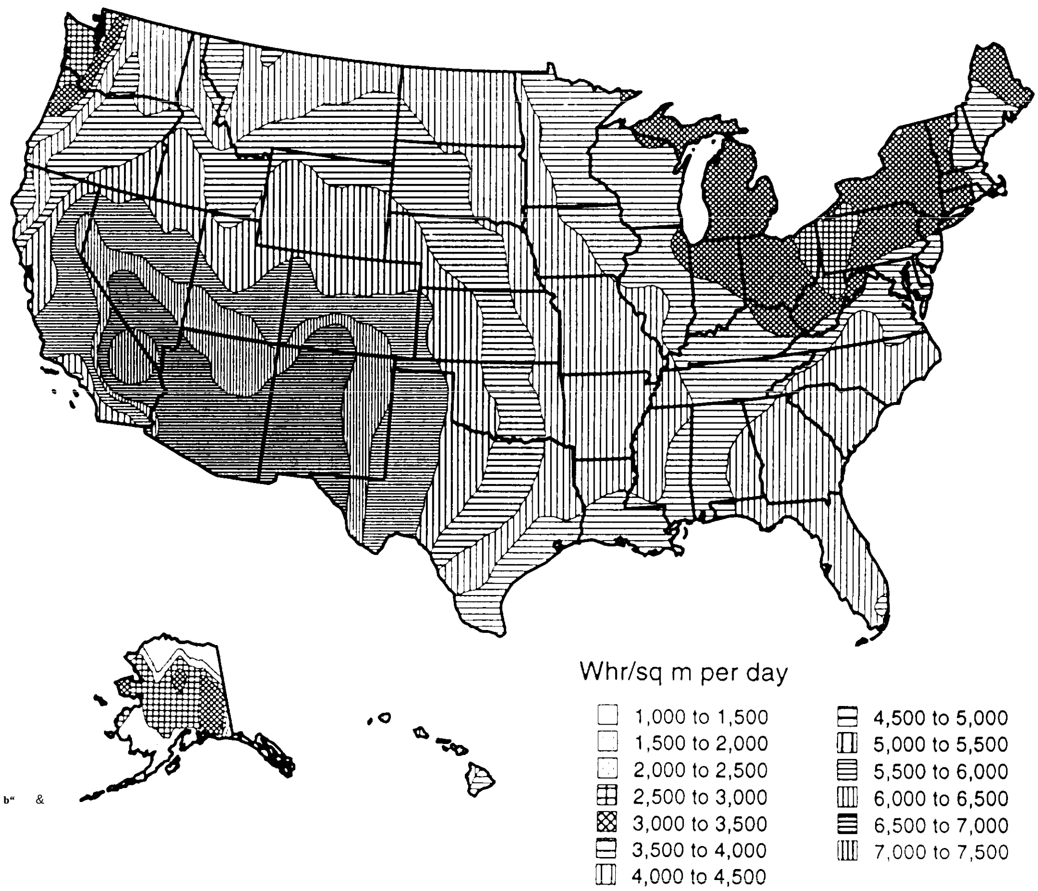
47 Electric *power Research Institute,* "Integrated *High-Concentration* Photovoltaic Technology," Technical Brief RP2948, 3256, December 1993.

BOX 5-6: Solar Resources and Collector Geometries

The solar resource varies hourly, daily, seasonally, geographically and with the local climate. Understanding this variation is important in choosing the best location and orientation for solar electric (photovoltalc or thermal) systems, for determining the optimum size of the solar system and of the associated (if any) storage system, and/or for matching the system output to the needs of the local utility, Detailed long-term records of insolation are needed for such evaluations

Sunlight at the Earth's surface has two components direct or beam radiation coming directly from the sun, and diffuse radiation that has been first scattered randomly by the atmosphere before reaching the ground. Together, these are known as the total or global radiation. In general, direct radiation is more sensitive to atmospheric conditions than diffuse radiation heavy urban smog might reduce direct radiation by 40 percent but total radiation by only 20 percent Direct solar radiation is shown in figure 1 and total radiation in figure 2,

Average Daily Direct (Beam) Solar Radiation, 1961-90



NOTE Direct solar radiation is the sunlight that comes directly from the sun to the receiver Values shown here are for direct sunlight on a surface always facing the sun—e g a surface that uses two axis tracking to follow the sun

SOURCE National Renewable Energy Laboratory 1993

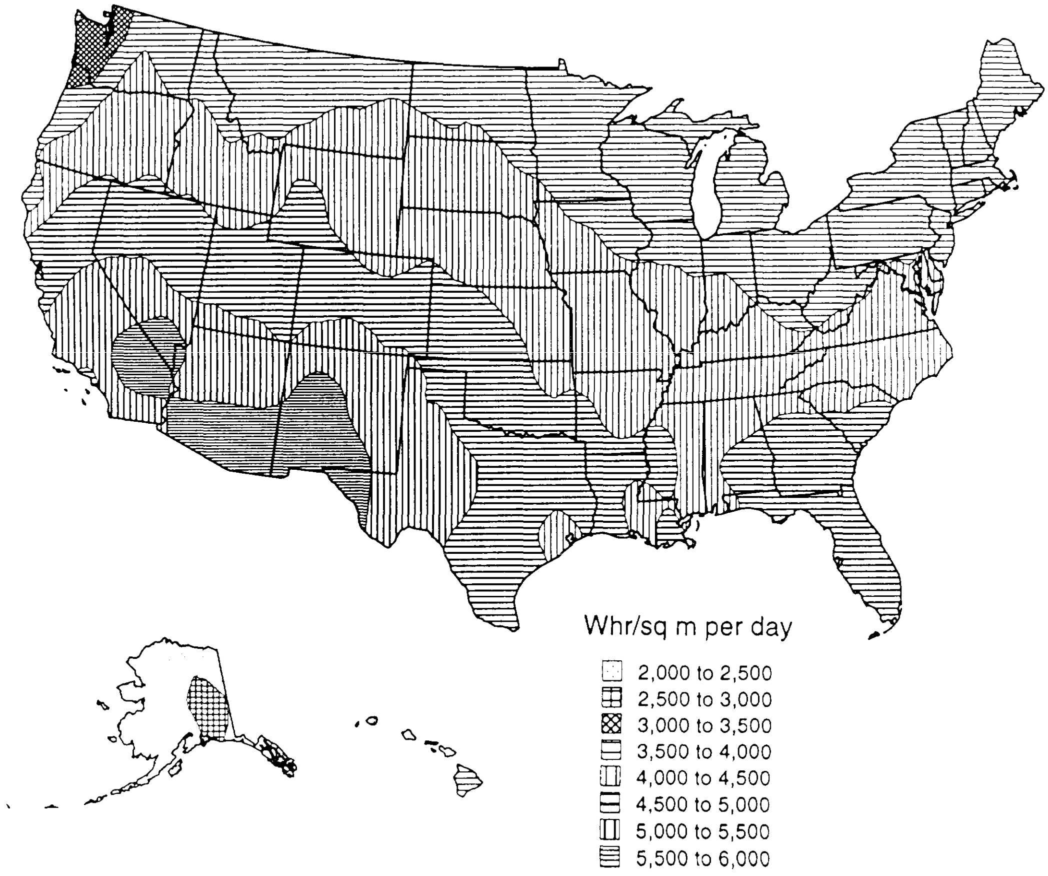
BOX 5-6 (cont'd.): Solar Resources and Collector Geometries

There are three general classes of solar collectors fixed, one-axis trackers, and two-axis trackers (figure 5-2) Fixed collectors are mounted in a fixed position and generally left there (although some may be adjusted seasonally) The amount of light Incident on the collector then changes over the day and season with the position of the sun relative to the orientation of the collector The specific orientation of the fixed collector IS adjusted to optimize the energy received-for example, to maximize winter or summer afternoon energy collection.

One-axis tracking collectors have one dlrection of movement—from east-to-west, for example—and so can roughly follow the sun's motion during the course of the day, but are not adjusted for the change in the suns position during the course of the year (or wee-versa for collectors adjusted north-south) Two-axis trackers can precisely follow the sun across the sky during the day and from one season to the next

Tracking collectors allow more direct sunlight to be captured per unit area of collector, but at a cost because of the moving parts and more complicated mounts Whether or not a tracking collector IS worthwhile depends on engineering and climatic factors, trading off the additional cost versus the value of the additional energy collected

Average Daily Total Solar Radiation, 1961-90



NOTE Total solar radiation Includes the sunlight coming directly from the sun plus that which comes from the sky Values shown here are for total solar radiation on a horizontal surface

SOURCE National Renewable Energy Laboratory, 1993

(continued)

BOX 5-6 (cont'd.): Solar Resources and Collector Geometries

Concentrating collectors must use tracking because the optics need careful orientation wtih respect to the sun. Use of concentrators, however, limits energy collection to direct radiation. Concentrators are therefore of greatest Interest in low humidity regions with relatively little scattering of direct sunlight, such as the U S Southwest. Some light is also lost by absorption in or scattering by the concentrating mirror or lens.

Although the solar resource is diffuse, the land areas required for electricity generation are similar to those for coal when mining is included (see table 1-2 in chapter 1), and are modest compared to the total U S land resource. For example, total U.S. electricity needs could be produced from less than 10 percent of the land area of Nevada. [1]

[1] John Thornton and Linda Brown, Photovoltaics The Present Presages the Future, " *The Electricity Journal,* April 1992, pp 34-41

take this risk. The Amoco/Solarex-Enron venture is an intermediate step that would both scale production up to 10 MW/year by 1997 and rely on a variety of tax supports to reach its cost goals. The leap in scale to achieve low-cost manufacturing is a very significant obstacle for PV manufacturers.

There are, however, a variety of high-value niche markets, such as remote or distributed utilit y applications (see below), for which PVs can effectively compete today. This provides near-term markets that can help scaleup manufacturing to the levels ultimately needed to compete for longer term bulk power markets. This perspective is becoming a key element of the PV industry strategy for scaling up manufacturing.

Research, Development, and Demonstration Needs

RD&D needs include further development in many areas: current PV materials and designs, including multiple junctions and composite materials; new materials and PV device structures; building-integrated PVs and other techniques to lower support structure and other costs; advanced manufacturing equipment; improved encapsulation technologies; lower cost and higher performance balance of system components; and better grid-integration technologies. Advanced manufacturing processes are an important element of a balanced RD&D portfolio. As demonstrated by the past 15 to 20 years of high-technology competition with Japan, manufacturing processes are, in many cases, as important as innovative devices. Continued R&D is an essential component of any PV development and commercialization strategy.

The PV industry, with total 1994 revenues of' roughly $150 million,[48] would not be able to fund RD&D at the $75 million amount that it received from the federal government in FY 94. Further, the record has shown very few deep-pocketed U.S. firms willing to support the long-term RD&D needed, despite the enormous potential of PVS. Foreign firms, however, have already purchased a number of U.S. PV firms (chapter 7) and are likely to purchase other important U.S. PV innovations and firms should the opportunity arise.

Estimates of the net present cost to bring PV technology to a competitive status versus conventional baseload equipment on an accelerated schedule (over the next 15 to 20 years) range

[48] Assuming $6,000/kW and 25 MW of PVs produced. See "Worldwide PV Shipments Top 60 MWp; U.S. in Lead But Europe Catching Up," *Solarletter, vol. 5, No. 6,* Feb. 17, 1995, p. 53.

BOX 5-7: Photovoltaic Technologies[1]

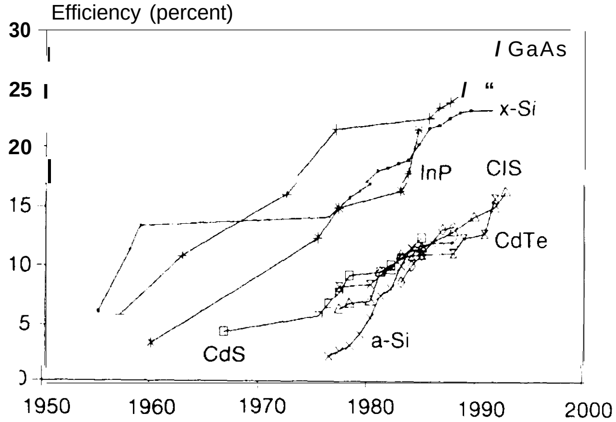
A PV cell is made by depositing layers of various materials so as to create an intrinsic (and permanent) electric field inside When light strikes the material, It can free an electron from weak bonds that bind it Once freed, the electric field then pushes the electron out of the PV and sends it through an external wire to do work—for example, to power a light, refrigerator, or an industrial motor—before returning to the PV cell, completing the circuit

The development of PVs presents difficult engineering choices between making the cell more efficient while keeping costs down. A number of technologies are used including thin-film flat plates, single crystal and polycrystalline flat plates, and concentrator systems These follow a progression from lower efficiency/ lower cost to higher efficiency/higher cost. At the current state of technology, all these approaches provide electricity roughly the same cost

Thin film PVs use little PV material—typical thicknesses of the film are 4/100,000 of an inch thick or 1/1 00 of a human hair—on a low-cost substrate such as glass, metal, or plastic Thin-film materials such as amorphous silicon (a-Si), copper indium dilselenide (CIS), and cadmium telluride (CdTe) potentially offer relatively high efficiency and easy fabrication (see figure 1) The efficiency of CIS is currently at 164 percent, the highest of any thin film, and stabilized large-area a-Si has reached 102 percent,[2] A joint venture between Energy Conversion Devices of Troy, Michigan, and Canon of Japan is constructing a manufacturing plant in Virginia to produce this high-efficiency a-Si, for which costs are expected to be 16¢/kWh in 1995, eventually dropping to 12¢/kWh [3]

Crystalline and polycrystalline flat-plate PVs of silicon are the most common and the most mature type of PV Nonconcentrating cells of silicon are now at 235 percent efficiency and nonconcentrating cells based on gallium arsenide (GaAs) have reached 295 percent.[4]

Efficiency of Photovoltaic Cells, 1954-94



NOTE: Shown here are the efficiencies of laboratory cells of single crystal silicon (x-Si), gallium arsenide (GaAs), indium phosphide (InP), cadmium sulfide (CdS), amorphous silicon (a-Si), cadmium telluride (Cd-Te), and copper indium diselenide (CIS). The wide range of PV materials, manufacturing processes, collector configurations, and systems designs provide confidence that some paths will succeed in reaching low-cost goals.

SOURCES: Paul Maycock, PV Energy Systems, Inc., personal communication, December 1993; Ken Zweibel, National Renewable Energy Laboratory, personal communication, January 1994; George Cody, Exxon Corporate Research Laboratory, personal communication, January 1994; and Masafumi Yamaguchi, "Present Status and Future Prospects of InP Solar Cells," paper presented at the 20th IEEE Photovoltaic Specialists Conference, 1988, Las Vegas, NV, Sept 26-30, 1988.

[1] An excellent overview of photovoltaic issues is provided by Ken Zweibel, *Harnessing Solar Power The Photovoltaics Challenge* (New York NY Plenum Press, 1990) a more recent and somewhat more technical review can be found in Thomas B Johansson et al (eds), *Renewable Energy Sources for Fuel and Electricity* (Washington, DC Island Press, 1993) A technical introduction to PV science is given by Martin A Green *Solar Cells Operating Principles, Technology and System Applications* (Englewood Cliffs NJ Prentice-Hall Inc 1982) For more detailed technical information on photovoltaic technologies, see IEEE Photovoltaic Specialists Conference European Community Photovoltaic Solar Energy Conference, and the Photovoltaic Science and Engineering Conference Each of these is held roughly every 18 months

[2] Anthony Catalano National Renewable Energy Laboratory personal communication May 3,1994

[3] Jerry Bishop New Silicon Cell Can Halve Cost of Solar Energy, " *Wall Street Journal* Jan 19, 1994 p B5

[4] Catalano op cit footnote 2

(continued)

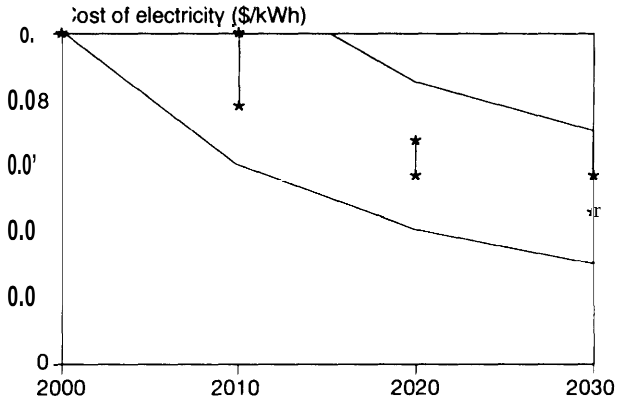
BOX 5-7 (cont'd.): Photovoltaic Technologies

Concentrator systems use low-cost mirrors or lenses[5] to focus light on a small, high-efficiency (but expensive) PV. Concentrator systems are more complex and are only able to use the direct component of sunshine. On the other hand, sufficiently low-cost lenses can compensate for the higher cost and complexity of tracking systems; sufficiently high-efficiency concentrator PVs can compensate for the loss of diffuse radiation and losses of light passing into and through the lens. Together, these can lower the overall cost of electricity from PVs. Because concentrator systems are more complex, they generally will need to be deployed in somewhat larger units than flat-plate PVs, which can be made use of in units as small as desirable.

Projected costs for photovoltaics are shown in figure 2. In the near to mid-term, these costs would make PVS competitive in a variety of niche markets, gradually expanding to important utility markets as costs continue to decline in the longer term, There are several factors that suggest that PVs will be able to meet these cost projections:

- *High efficiencies,* PV cells under development have demonstrated efficiencies sufficiently high to make these costs potentially achievable. Good progress has also been made in translating laboratory advances into commercial products, although the lag time is often five years or more.
- Alternative paths. There are numerous alternative PV materials and manufacturing processes, as well as many system designs, providing confidence that at least some technology and engineering paths will prove successful in reaching these goals.

Cost Projections for Photovoltaic-Generated Electricity



NOTE: The cost of PV-generated electricity is expected to drop to the range of 10¢ to 20¢/kWh by the year 2000, and continue to decline rapidly in following years depending in large part on the scale of manufacturing. Longer term cost reductions also depend on lowering the costs of other system components and installation methods. Some recent projections indicate costs could be lower by the year 2000. The shaded range encloses most of the expert estimates reviewed, with all estimates in constant 1992 dollars and, where necessary, capital cost and other estimates converted to ¢/kWh using discount rates of 10 and 15 percent (with 3 percent inflation). High and low values developed by the Department of Energy are shown as *.

SOURCE: Office of Technology Assessment, based on: U.S. Department of Energy, "Renewable Energy Technology Evolution Rationales," draft, October 1990; Thomas B. Johansson et al. (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993); John Doyle et al., *Summary of New Generation Technologies and Resources* (San Ramon, CA: Pacific Gas and Electric Co., 1993); and Bechtel Group, Inc., *Engineering and Economic Evaluation of Central-Station Photovoltaic Power Plants*, EPRI TR-101255 (Palo Alto, CA: Electric Power Research Institute, December 1992).

[5] Lenses are generally used with PVs while mirrors are generally used with solar thermal systems The reason for this difference in approach is that concentrating cells need to be cooled m order to maintain their high efficiency Passive cooling technologies are preferred due to their simplicity, but these require large heat fins to allow effective convective heat transfer With a mirrored system, these large heat fins would naturally lie between the sun and the mirror, blocking some of the incoming sunlight With lenses, these heat fins naturally lie behind the cell and thus do not cause any shading. In addition, PVs are sensitive to hot spots—where the light is more highly concentrated—due to imperfections in the mirror or lens. Such imperfections are more easily controlled with lenses than with mirrors.

BOX 5-7 (cont'd.): Photovoltaic Technologies

- *Low-cost materlas.* Both thin-film and concentrator PVs use very small amounts of active electronic materials This minimizes the cost of production
- Design studies Detailed engineering design estimates for the near to mid-term show that dramatic cost reductions are possible with just modest improvements in commercial products and the advantages of mass productlon,[6]
- Additional *manufacturing cost reductions* Will include Improvements in polycrystalline ingot casting, improved sawing for slicing ingots; the development of ribbon technologies to improve handling of wafers and reduce silicon waste, Innovations to allow continuous deposition of thin film PV layers; and various strategies for reducing the cost of solar-grade silicon

Environmental Impact

A variety of toxic chemicals are used in the manufacture of PVs, but emisslon of these toxics are routinely minlmlzed[7] and PV production facilities pose little risk for their surroundings Although some toxic materials such as arsenic and cadmium are contained within some types of PVs, studies indicate that they are well Immobilized within the cell and pose very little threat to the environment [8] PVs also generate no greenhouse gas emissions during operation, Overall, PVs are perhaps the most enbotonmentally benign of all the renewable energy technologies

6 W J Stolte, "Engineering and Economic Evaluation of Central-Station Photovoltaic Power plants, ' EPRI f+@ TR-101255 December 1992 Daniel S Shugar et al Pacific Gas & Electric Co , Comparison of Solar Thermal Troughs with Photovoltaics as a PG&E Central Statlon Resource in the 1990s " 1991 Yutaka Hayashi et al 'Design Option for a Crystalline Silicon Solar Cell "*Technical Digest of the International PVSEC-5* (Kyoto Japan 1990), G Darkazalli et al "Sensitivity Analysis and Evaluation of Manufacturing Cost of Crystalline Silicon PV Modules paper presented at the 22nd IEEE Photovoltaic Specialists Conference Las Vegas NV, October 1991, D E Carlson, Low-Cost Power from Thin-Film Photovoltaics" Johansson et al (eds) op cit footnote 1 J Wohlgemuth et al Solarex Corp 'Cost Effectiveness of High Efficiency Cell Processes as Applied to Cast Polycrystalline Silicon ' n d and Paul D Maycock, personal communications, 1992 and 1993

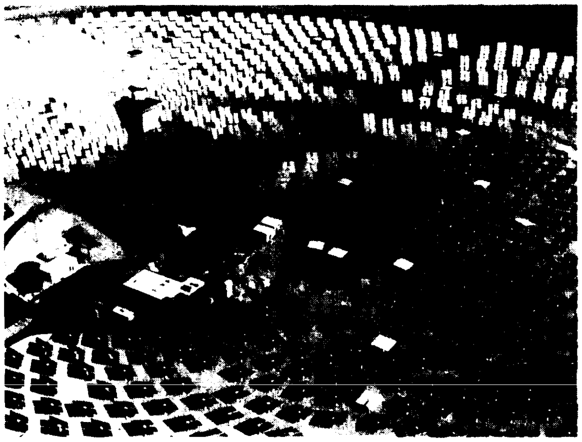
7 P D Moskowitz et al Safety Analysis for the Use of Hazardous Productlon Materials in Photovoltaic Applications Advances *in Solar Energy* vol 8, Morton Prince (ed) (Boulder CO American Solar Energy Society, 1992), pp 345-396

8 Kenneth Zweibel and Richard Mitchell "CuInSe$_2$ and CdTe Scale-up for Manufacturing, " *Advances in Solar* Energy, vol 6 Karl W Boer (ed) (Boulder Co American Solar Energy Society 1990) pp 485-579

around $5 billion to $9 billion (globally) for both additional RD&D and commercialization supports.[49] Such estimates are based on rough extrapolations of the observed learning curve for PV and other industries. Estimates of the return on R&D specifically have not been possible, however, given currently available data.[50] Although this is a Significant expenditure, it is just one-fifth to one-tenth that projected for the U.S. investment alone

49 G.D. Cody and T.J. Tiedje, "The Potential for Utility Scale Photovoltaic Technology in the Developed World: 1990-2010, " *Energy and the Environment*, B. Abeles et al. (eds.) (River Edge, NJ: World Scientific Publishing Co., 1992); World Energy Council, *Renewable Energy Resources, Opportunities and Constraints 1990 -2020* (London, England: September 1993); and Robert H. Williams and Gregory Terzian, *A Benefit/Cost Analysis of Accelerated Development of Photovoltaic Technology*, Report No. 281 (Princeton, NJ: Center for Energy and Environmental Studies, October 1993).

50 Kenneth Richards, *Dynamic Optimization of the Photovoltaic Commercialization Process* (Washington, DC: Battelle, pacific Northwest Laboratories. June 30, 1993), p. 51 and following.



SOLAR ENERGY INDUSTRIES ASSOCIATION

The Solar One Central Receiver test facility in California. This 10-MW facility provided much valuable data over six years of testing and is now being upgraded to test improved receivers and thermal storage, heliostat design, and other technologies.

to develop a prototype fusion reactor and determine the technical and commercial feasibility of that energy resources.[51]

Solar Thermal

Solar thermal electric plants use mirrors to concentrate sunlight on a receiver holding a fluid or gas, heating it, and causing it to turn a turbine or push a piston coupled to an electrical generator.[52] Solar resources are described in box 5-6 and solar thermal technologies are described in box 5-8. The basic forms of solar thermal collectors are shown in figure 5-2.

Some 354 MW of solar parabolic trough thermal powerplant capacity were installed in California's deserts between 1984 and 1991, and demonstrated increasing reliability and performance and decreasing costs with each generation. The levelized cost of electricity for the most recent generation of plant dropped to roughly 10¢ to 12¢/kWh, with expectations that the next generation plant could reach costs as low as 8¢/kWh.[53] Further development of this type of solar thermal electric system has been significantly delayed by the bankruptcy of Luz, Inc., in 1991 (see chapter 6).[54] This experience showed, however, that solar thermal is a technically viable option and could potentially be cost-competitive with many fossil systems.

The Solar One Central Receiver[55] similarly performed well, achieving 99 percent heliostat availability and 96 percent overall availability for the entire powerplant.[56] Its energy production was somewhat lower than predicted, however, and the next generation system now in planning and development, Solar Two, has been designed to sidestep this problem.[57] Advances have been made and tested on direct-absorption receivers, heliostat design and materials, and other components.

Parabolic dish systems have also seen considerable advances, including the development of stretched membranes dishes, advanced receivers, and long-lived stirling engines. Small 7 kW systems are now being developed by Cummins Pow-

51 U.S. Congress, Office of Technology Assessment, *The Fusion Energy Program: Next Steps for TPX and Alternate Concepts*, OTA-BP-ETI-141 (Washington, DC: U.S. Government Printing Office, February 1995).

52 In some cases, the solar heated fluid or gas may pass through a heat exchanger and heat a separate fluid or gas that actually turns the turbine.

53 This includes cofiring with natural gas.

54 For a history of why Luz went bankrupt, see Michael Lotker, *Barriers To Commercialization of Large-Scale Solar Electricity: Lessons Learned from the Luz Experience*, SAND91-7014 (Albuquerque, NM: Sandia National Laboratory, November 1991); and Newton Becker, "The Demise of Luz: A Case Study," *Solar Today*, January/February 1992, pp. 24-26.

55 This system was commissioned in 1982 and shut down in 1988.

56 Richard B. Diver, "Solar Thermal Power: Technical Progress," in *Progress in Solar Energy Technologies and Applications: An Authoritative Review* (Boulder, CO: American Solar Energy Society, January 1994).

57 Power generation by Solar One was lowered in large part due to passing clouds causing the generator to trip off-line. In Solar Two, this is being avoided primarily through the use of molten salt thermal storage, which will provide energy through disruptions by passing clouds.

er Generation, a subsidiary of Cummins Engine Company, in a joint venture with DOE/Sandia National Laboratory and are slated for commercialization in 1996.

Parabolic trough and central receiver systems are generally large-scale systems, typically 50 to 200 MW, and so will be operated much as conventional large-scale fossil plants are today. Parabolic dish systems can be operated in small units and can then be used in remote or distributed utility applications (see below); larger dishes could be operated in large-scale grid connected systems. All of these systems can be operated as hybrids. most often using natural gas to supplement and extend the solar energy that is collected. This is particularly important for extending power output into evening peak hours.

The solar thermal electric industry consists of a mix of large and small firms. Luz, a relatively small independent firm, was the primary developer of parabolic trough systems until its bankruptcy. Unable to interest utilities in buying turnkey projects,[58] Luz turned to manufacturing, developing, and operating parabolic trough systems itself, with financing from large institutional and corporate investors. Following the bankruptcy of Luz, the investors formed or contracted separate operating companies to maintain and operate the plants at Kramer Junction, Daggett, and Harper Lake, California. Although much interest has been expressed around the world in developing additional parabolic trough systems, with a number of feasibility studies under way, no firm commitments have yet been made.[59]

Central receivers have been primarily supported by large firms such as Bechtel and Rockwell International, although some small firms such as Advanced Thermal Systems have also played roles. Currently, central receiver development is proceeding through the 10-MW Solar Two project, cost-shared between DOE and a number of utility and other partners, including Southern California Edison, Sacramento Municipal Utility District, Los Angeles Department of Water and Power, Idaho Power Company, Pacific Gas and Electric, Electric Power Research Institute, and Bechtel. At least three firms-Bechtel, Rockwell International, and Science Applications International—are developing a joint business plan for commercializing 100- to 200-MW central receivers in the late 1990s.

Dish stirling systems are now receiving considerable support from large companies such as Cummins Engine, Detroit Diesel. and Science Applications International, as well as by small firms such as Solar Kinetics, Accurex, and Industrial Solar Technology. There is a significant industry commitment, cost-shared with the federal government, to commercializing this technology. Cummins Power Generation, a subsidiary of Cummins Engine, has been developing a small-scale (7-kW) parabolic dish system since 1988; commercialization is planned in 1996. Under the Utility-Scale Joint-Venture program, Science Applications International and others are developing a 25-kW dish system that is expected to produce power at 6~/kWh; commercialization is planned for 1997. Some 56 dish systems will be manufactured and demonstrated at U.S. utilities under this program.

Research, Development, and Demonstration Needs

RD&D needs include better materials and lifetimes for stretched membrane mirrors and other optics, improved selective surfaces, advanced receiver designs, long-lived and high-efficiency stirling and other engines, and improved control systems. Much of this RD&D is focused on basic materials issues beyond the scope of individual firms now developing solar thermal systems.

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58 Hamrin and Rader, op. cit., footnote 7.

59 Countries currently examining the feasibility of installing parabolic trough plants, with some already applying for World Bank support, include: India, Iran, Israel, Mex ice, Morocco, and Spain. David Kearney, Kearney and Associates, personal communication, Au:. 24, 1994.

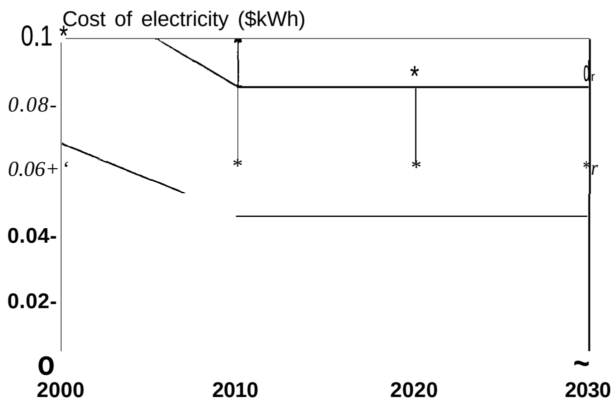
BOX 5-8: Solar Thermal Technologies

Solar thermal systems are typically categorized by the type of collector used parabolic trough, central receiver, parabolic dish, and solar pond, '

Parabolic trough systems currently account for more than 90 percent of the world's solar electric capacity. These systems have long (100 meters or more) trough-shaped mirrors with a tube at the focal line along the center The trough tracks the sun's position in the sky. The tube is clear glass with a black metal pipe carrying heat-absorbing fluid down the middle. To minimize heat loss from the black absorbing pipe back to the outside, the pipe has special coatings (selective surfaces) that reduce the amount of heat it radiates and the space between the absorbing pipe and the glass tube is evacuated to prevent heat conduction by air molecules. The fluid heated in the pipe is then pumped to where it can either indirectly (through a heat exchanger) or directly expand through a turbine to generate electricty. The potential of solar troughs is limited by the relatively low concentration ratios and receive temperatures (400°C or 750°F) that can be realized, leading to relatively low turbine efficiencies,

Central receivers have a large field of mirrors, known as heliostats, surrounding a fixed receive mounted on a tower. Each of the heliostats Independently tracks the sun and focuses light on the receiver where it heats a fluid or gas This fluid or gas is then allowed to expand through a turbine, as before, Key technical developments have been the development of stretched membrane mirrors to replace the glass and metal mirrors previously used.[2] The stretched membrane consists of a thin sheet of highly reflective material (plastic) held in a frame and curved to the desired shape.[3] They weigh much less than the glass and metal mirrors used previously, saving materials and reducing the weight on and the cost of the supporting frame. Stretched membranes have been developed that hold up well

Cost Projections for Solar Thermal



NOTE. The cost of solar thermal—parabolic trough, central receiver, and parabolic dish—generated electricity is expected to drop to the range of 7¢ to 12¢/kWh by the year 2000, with long-term costs of 4.5¢ to 9¢/kWh for the more efficient central receiver and parabolic dish systems, depending on the particular technology, the use of storage or natural gas backup, and other factors. The shaded range encloses most of the expert estimates reviewed, with all estimates put in constant 1992 dollars and, where necessary, capital cost and other estimates converted to ¢/kWh using discount rates of 10 and 15 percent (with 3 percent inflation). High and low values developed by the Department of Energy are shown as *.

SOURCE: Office of Technology Assessment, based on: U.S. Department of Energy, "Renewable Energy Technology Evolution Rationales," draft, October 1990; Thomas B. Johansson et al. (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993); and John Doyle et al., *Summary of New Generation Technologies and Resources* (San Ramon, CA: Pacific Gas and Electric Co., 1993).

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[1] Solar pond systems use a large shallow pond with a high density of dissolved salt to absorb and trap heat at the bottom, they do not use concentrating mirrors An extensive network of tubes then circulates a special fluid 10 absorb this heal The fluid then expands and turns a turbine Because of the very low temperatures revolved, typically around 90°C, solar pond systems are necessarily very low efficiency and require extensive piping networks to capture the heat absorbed Solar @rids also use huge amounts of water, perhaps 30times that of a conventional powerplant Their costs are likely to remain high for the foreseeable future and their applications are likely to be limited; they will not be considered further here DOE funding for solar ponds was terminated in 1983

[2] Some are examining mirror systems consisting of, for example, plastic membranes and glass reflecting elements

[3] The space behind the stretched membrane is typically partially evacuated, i e held at a lower air pressure, so that the air pressure outside pushes the membrane into a curve that focuses the light

BOX 5-8 (cont'd.): Solar Thermal Technologies

to gusty winds, but overall lifetimes are still short (5 to 10 years), the reflective coating is easily scratched, and effective low-cost cleaning techniques could use further refinement The design of the receiver is also undergoing extensive research, with much of the emphasis on molten salts as the working fluid. The molten salt would provide thermal storage to allow better matching of system output to utility needs and to carry system operation through brief passing clouds Central receivers achieve temperatures of typically 650°C (1 ,200°F)

Parabolic dish systems use a large dish or set of mirrors on a single frame with two-axis tracking to reflect sunlight onto a receiver mounted at the focus, Most commonly, a free piston stirling engine is mounted on the receiver, but hot fluids can also be piped to a central turbine as in the parabolic trough and central receiver systems Current research is focusing on lowering the cost of the mirror systems through the use of stretched membranes and to Improve the reliability and performance of the stirling engine.[4] Stirling engine lifetimes of 50,000 hours (about 10 years) with little or no maintenance are needed and are being developed.[5] In comparison, the typical automobile engine must have minor maintenance every 250 hours or so, and a major overhaul perhaps every 2,500 hours. [6] Parabolic dishes can achieve the highest temperatures (800°C or 1,500°F) and thus the highest efficiencies of concentrating solar thermal systems Parabolic dish systems currently hold the efficiency record of 31 percent (gross) and 29 percent (net) for converting sunlight into electricity [7]

All of these systems concentrate the sunlight to increase the operating temperature of the absorbing fluid and thus increase the efficiency of the turbine or engine that is driven, Concentration works only with the direct beam component, so regions with clear, dry air—such as the American Southwest—are preferable, although operation in other climates is possible [8]

Central receiver and parabolic dish systems have higher concentration ratios than solar troughs, and therefore the potential to achieve higher efficiencies and lower costs for generated electricity Projected costs for solar thermal technologies generally are shown in the figure and are expected to be competitive with fossil systems in a variety of applications in the mid- to longer term.

Environmental Impact

Solar thermal technologies can potentially impact the environment in several ways, including affecting wildlife habitat through land use, using large amounts of water in arid regions, or releasing heat transfer fluids or other materials into the environment, Proper siting and controls can minimize these potential impacts Natural gas cofiring produces nitrogen oxides and carbon dioxide emissions, but these emissions would be proportionately less for a solar thermal hybrid than for conventional fossil fuel use alone Overall environmental impacts appear to be quite low

[4] Charles W Lopez and Kenneth W Stone, "Design and Performance of the Southern California Edison Stirling Dish, " *Solar Engineering*, vol 2 1992, pp 945-952, and Graham T Reader and Charles Hooper, *Stirling Engines* (New York, NY E & F N Spon 1983)

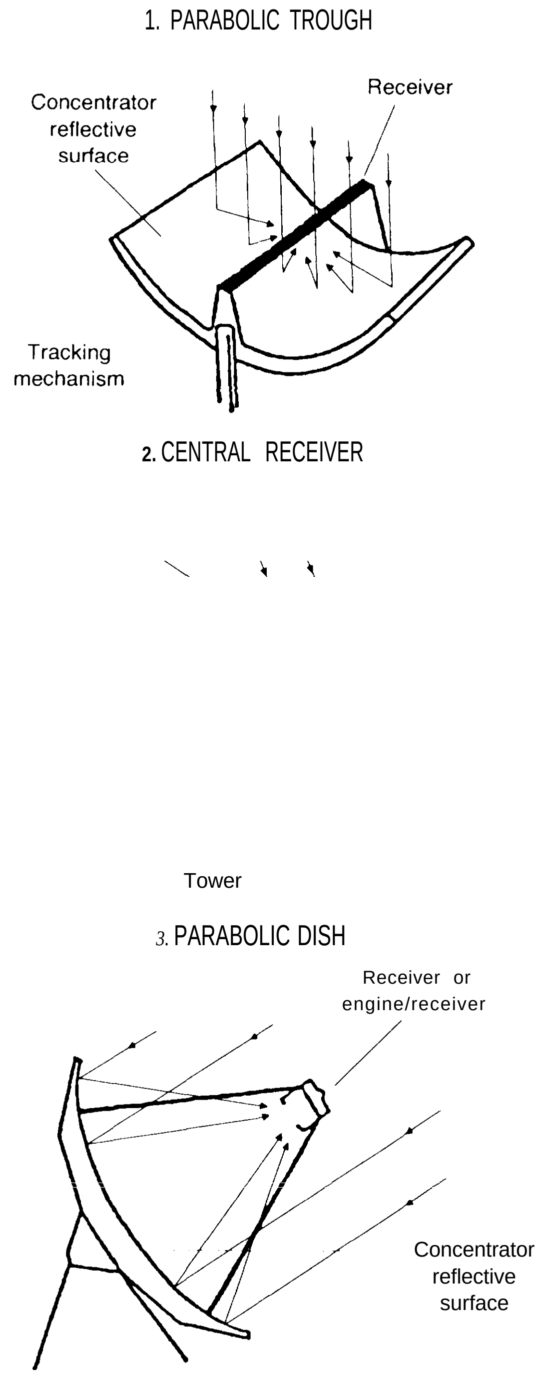
[5] Pascal De Laquil III et al "Solar Thermal Electric Technology, " *Renewable Energy Sources for Fuels and Electricity*, Thomas B Johansson et al (eds) (Washington DC Island Press, 1993)

6 For an automobile, an 011 change every 7,500 miles corresponds to 250 hours of operation, assuming an average operating speed of 30 mph Similarly a major overhaul every 75,000 miles corresponds to 2,500 hours of operation

7 William B Stine, Progress *in Parabolic D@ Technology*, SERI/SP-220-3237 (Golden, CO Solar Energy Research Institute, June 1989)

8 For example a dish stirling project has been operated in Lancaster Pennsylvania to pump water See "Solar Thermal Power Generation Is Viable in the Northeast *Solar Industry Journal*, vol 3, No 4, 1992, pp 14-15

FIGURE 5-2: Solar Thermal Collectors



SOURCE: Office of Technology Assessment, 1995.

Wind

Wind energy systems use the wind to turn their blades, which are connected to an electrical generator. Wind energy resources and technologies are described in box 5-9.

Wind technology improved dramatically during the past decade. Costs for wind-generated electricity were reduced from over $ l/kWh in 1981 to 5¢ to 6¢/kWh today, with the best plants now coming in as low as 4.3¢/kWh on a real levelized basis in areas with high-quality wind resources.[60] A number of factors contribute to these gains, including: advances in the design of wind turbine blades (15 to 30 percent energy gain); advances in and cost reductions of power electronics (5 to 20 percent energy gain); improved designs and materials to lower operations and maintenance costs; and better understanding of wind energy resources and siting needs. More than 1,700 MW of wind capacity were installed in California, where more than 1.5 percent of all electricity consumed is now generated by the wind---enough electricity to supply all the residential needs of one million people. Worldwide, a wind capacity of 3,200 MW is now connected to electricity grids.[61] wind systems are now poised to enter large-scale markets in many areas. Recent U.S. commitments include Northern States Power for 425 MW, Lower Colorado River Authority for 250 MW, and Portland General Electric for 100 MW.

Wind systems provide intermittent power according to the availability of wind. Small, standalone wind systems, often backed up with battery storage, can be used in a variety of remote applications. Large wind turbines can be sited individually, or more commonly in "wind farms," and connected to the electricity grid. The extent to which wind power can offset other electricity-generating capacity then depends on its match

60The Northern States Power 25-MW project now online costs 4.7¢/kWh and the Sacramento Municipal Utility District system 4.3¢/kWh. Randy Swisher, American Wind Energy Association, personal communication, May 1994.

61Gerald W. Braun and Don R. Smith, "Commercial Wind Power: Recent Experience in the United States," *Annual Review Of Energy and [he Environment, vol. 17, 1992,* pp. 97-121.

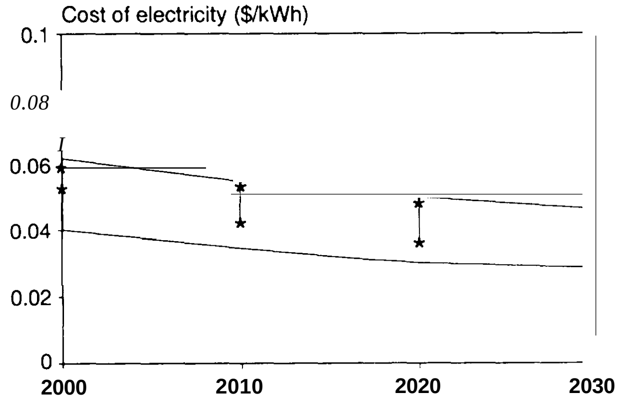
BOX 5-9: Wind Energy Resources and Technologies

Three key factors distinguish wind energy resources the variation in the power of the wind with its speed, the variation in available wind speeds at a given site over time periods ranging from seconds to months, and variations in wind speed with height above the ground. These have Important implications for wind turbine design and operation.

The power available in the wind Increases with the cube, i.e. V^3, of the wind speed Because of the factor V^3, wind turbines must handle a huge range of power. From the speed at which the turbine reaches its rated power to the speed at which the turbine is stopped (cut-out speed) to prevent damage, the power in the wind Increases by typically more than six times This variation in wind power with wind speed has led to the development of a variety of techniques to aid efficient collection of power at low speeds and to lilmit and shed excess wind power from the turbine blades at high speeds. Because the wind rarely blows at very high speeds, building the wind turbine strong enough to make full use of high winds is not worthwhile,

The sensitivity of wind power to wind speed also requires extremely careful prospecting for wind sites. A 10-percent difference in wind speeds gives a 30-percent difference m available wind power.

Cost Projections for Wind Energy



NOTE The cost of wind-generated electricity has dropped from over $1/kWh in 1981 to as low as 4.3¢/kWh in 1994, and is expected to continue to drop to 3¢ to 4¢/kWh for a large range of wind resources by 2030 The shaded range encloses most of the expert estimates reviewed, with all estimates put in constant 1992 dollars and, where necessary, capital cost and other estimates converted to ¢/kWh using discount rates of 10 and 15 percent (with 3 percent inflation) High and low values developed by the Department of Energy are shown as *

SOURCE Off Ice of Technology Assessment, based on U S Department of Energy, "Renewable Energy Technology Evolution Rationales ' draft, October 1990, Thomas B Johansson et al (eds.), *Renewable Energy Sources for Fuels and Electricity* (Washington, DC Island Press 1993), and John Doyle et al *Summary of New Generation Technologies and Resources* (San Ramon, CA Pacific Gas and Electric Co , 1993)

Wind speeds can vary dramatically over the course of seconds and minutes (turbulence), hours (diurnal variation), days (weather fronts), and months (seasonal varilatlons), The best Iocations are those with strong, sustained winds having little turbulence Finding such Iocations requires extensive prospecting and monitoring

Although the power output of any particular wind turbine will fluctuate with wind speed, the combination of many wind turbines distributed over a geographic area will tend to smooth out such fluctuations. This "geographic diversity" is an Important factor in system Integration. On the other hand, in a large array of wind turbines—a "wind farm"—the Interference of one wind turbine with its neighbors must be taken into account by carefully spacing and arranging the turbines.[1]

Winds also vary with the distance above ground level, this is known as "wind shear" Typically, winds at 50 meters will be about 25 percent faster and have twice the power as winds at 10 meters. The cost-effectivess of tapping these higher winds is then a tradeoff between the cost of the higher tower and the additional power that can be collected.

[1] Michael J Grubb and Niels I Meyer "Wind Energy Resources Systems, and Regional Strategies *Renewable Energy Sources for Fuel and Electricity*, Thomas B Johansson et al (eds) (Washington, DC Island Press, 1993)

(continued)

BOX 5-9 (cont'd.): Wind Energy Resources and Technologies

Wind shear places great stress on turbine blades. For a rotor with a diameter of 25 meters and its center (hub) 25 meters off the ground, the variation in wind speed with height above the ground will result in a nearly 50-percent variation in wind power between the top and bottom of the rotor arc. This, plus the effects of gravity, wind turbulence (gusts), the "tower shadow" on down-wind turbines, and other factors, severely flexes and thus stresses the rotor during every revolution. Over a 20- to 30-year Iifetime, the rotor will go through perhaps 500 million such stress cycles.[2] This is a level of stress that is virtually without equal in humanmade systems, and poses severe requirements on rotor materials and blade design,[3]

Locations with favorable wind resources in the lower 48 states are shown m figure 5-3. The plains states have a particularly large available wind resource, with the potential to generate 1.5 times as much electricity as is currently consumed in the United States. Large wind resources have also been found in many other countries.[4]

Technology

Wind turbines take two primary forms defined by the orientation of their rotors the familiar propeller style horizontal axis wind turbine (HAWT) and the less common vertical axis wind turbine (VAWT).[5] The HAWT accounts for over 93 percent of the Installations in California.

Turbine blades must manage the very high levels of stress, described above, while efficiently collecting energy; they must do so with long lives and at low installed cost. To meet these demanding criteria, designers have turned to innovative designs[6] and materials for the turbine blades. Researchers at the National Renewable Energy Laboratory, for example, have developed a new family of blade designs that produce an overall 30-percent annual energy gain compared to conventional blades and are relatively unaffected by roughness due to dirt and bugs, yet automatically Iimit rotor peak power at high winds much more effectwely than conventional blades.[7] Composite materials such as fiberglass and wood/epoxy now account for most rotor blades currently in use in California,[8] and researchers are Iooking to advanced materials for blade construction.[9]

2 Based on a 4,000-hour Operation per year, a rotational speed of 35 or 70 rpm For example, N = (70 rpm)*(60 minutes/ hour) *(4,000 hours/year)* (30 years) = 500 million

3 National Research Council, Assessment *of Research Needs for Wind Turbine Rotor Materials Technology* (Washington, DC National Academy Press, 1991)

4 Strategies Unlimited, "Study of the Potential for Wind Turbines in Developing Countries, " March 1987 The identified countries Include Argentina, Brazil, Chile, China, Colombia, Costa Rica, India, Kenya, Pakistan, Peru, Sri Lanka, Tanzania, Uruguay, Venezuela, Zambia, and Zimbabwe; California Energy Commission, "Renewal [sic] Energy Resources Market Analysis of the World, " CEC P500-87-015, n d , p 34

5 FloWind is currently working on an advanced VAWT with DOE and has prototypes under test at Tehachapi, CA

6 Rotor blades typically take a variety of forms They maybe rigid with a fixed pitch (fixed orientation), but with a specially designed blade shape to limit how much energy they capture from the wind They may have a variable pitch, in which the blade is rotated along its long axis in order to change the blade orientation with respect to the wind and thus limit energy capture They may be teetered, in which the rotor hub is allowed to rock up or down slightly in order to reduce stress on the drivetrain They may have ailerons built m, like flaps on an airplane wing, to control them More advanced forms may use small holes in the surface of the blade through which air can be blown to control the aerodynamics of the blade Each of these has certain advantages and disadvantages in terms of complexity, cost, performance, stresses, excess vibration, and other factors Alfred J Cavallo et al , "Wind Energy Technology and Economics, " in Johansson et al (eds.), op cit , footnote 1, and National Research Council, op cit footnote 3

7 J Tangier et al, *Measured and Predicted Rotor Performance for the SERI Advanced Wind Turbine Blades* (Golden, CO National Renewable Energy Laboratory, n d), and J Tangier et al *SERI Advanced Wind Turbine Blades* (Golden, CO National Renewable Energy Laboratory, February 1992)

8 Gerald W Braun and Don R Smith, "Commercial Wind Power Recent Experience in the United States, " *Annual Review of Energy and the Environment, VOI* 17, 1992, pp 97-121

9 National Research Council, Op cit , footnote 3

BOX 5-9 (cont'd.): Wind Energy Resources and Technologies

A particularly Important development is the use of advanced electronics to convert variable frequency power0[10] into a constant voltage and frequency for the electricity grid. Developed and marketed for large-scale wind turbines in the United States by Kenetech-U. S. Windpower—they received an R&D 100 award in 1993 for this technology—and others,[11] such systems reduce the cost of wind-generated electricity in two ways Variable-speed systems have a higher conversion efficiency at a lower wind speed and maintain it over a broader wind speed range, allowing more wind energy to be captured. They also greatly reduce the stresses on the rotor and drivetrain---allowmg them to be downsized and cutting their capital costs and maintenance requirements.

The capital and operations and maintenance costs for large grid-connected wind turbines have been dropping steadily throughout the 1980s. The capital cost of large turbines has already dropped to as low as $850/kW [12] The best wind turbines in California achieve a 97-percent availability Capacity factors depend on the wind at the site, but some are as high as 40 percent.[13] Projected electricity costs are shown in the figure; [14] these are potentially highly competitive.

Environmental Impact

Large land areas are required for siting wind farms, but the turbines, access roads, and related equipment *rarely* take more than 5 percent of the actual land area. The remainder can continue to be used for farming, ranching, or other purposes with little or no change Land values have substantially Increased in Altamont pass in California due to the additional income generated by royalties from the wind turbines

Noise was a problem with some early windmill designs. For the current generation of windmills, the noise problem is often no longer significant, in Denmark, for example, regulations limit windmlll-generated noise at the nearest dwelling to less than that found inside a typical house during the day A single 300-kW wind turbine can meet this standard when sited just 200 meters from the home, 30 such machines would need to be sited 500 meters away. [15]

Bird kills due to hitting the rapidly turning rotor blades have been a problem in some areas, including Altamont pass where raptors have been killed Some studies have concluded that these bird kills are substantially less than those from high voltage transmission lines, radio and TV towers, highway collisions with cars, or other such hazards.[16] Nevertheless, bird kills are of ongoing concern and efforts to understand and reduce this problem are under way

In some areas, particularly those with a high scenic value, the visual impact of wind farms may also be a concern

10 Current turbine designs fix the rate of rotation of the rotor to a specific speed corresponding to the 60-cycle frequency of the utility grid

11 Such systems have been used in Europe for several years and have been used on Small wind turbines in the United States and elsewhere for more than a decade Paul Gipe "Windpower's Promising Future, " *Independent Energy,* January 1993 pp 66-72

12 Dale Osborne, Kenetech Inc , personal communication, Mar 22, 1993

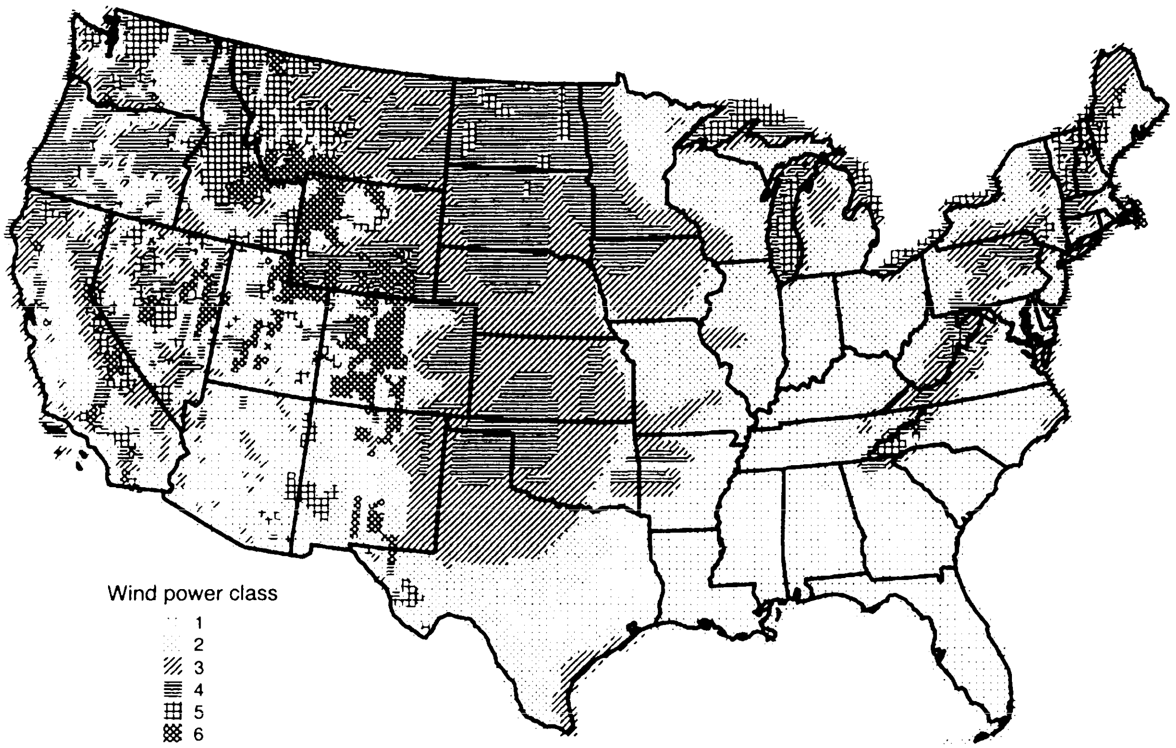
13 The Whitewater Hill site outside Palm Springs reportedly has a capacity factor of 40 percent Randy Swisher, American Wind Energy Association, personal communication, May 23, 1994

14 Al Cavallo, in Johansson et al (eds), op cit footnote 1

15 Michael J Grubb and Niels I Meyer, "Wind Energy Resources, Systems, and Regional Strategies, " in Johansson et al (eds), op cit footnote 1

16 A J M van Wijk et al World Energy Council, Study Group on Wind Energy, "Wind Energy Status, Constraints and Opportunities," sixth draft, July 1992, and Paul Gipe, Paul Gipe and Associates, "Wind Energy Comes of Age m California " n d

FIGURE 5-3: Average Annual Wind Resources



SOURCE. D.L. Elliott, Pacific Northwest Laboratory, "Wind Energy Resource Atlas of the United States," Nov. 8, 1994.

with the utility load and potential complementary combinations with other generation resources. Selecting wind sites with good matches to the utility load and gathering wind over a wide geographic area or combining it with other intermittent RETs (iRETs) such as solar may substantially smooth its variability.

The wind industry was strongly driven during the early to mid- 1980s by the Public Utility Regulatory Policies Act, federal and state tax credits, and by California Standard Offer 4 contracts. Initially, with extensive tax benefits available, projects were often financed through third-party limited partnerships; following the reduction in tax benefits, support has been provided more by institutional investors in non-recourse project financing (see chapter 6).

By one estimate, more than 40 wind energy developers installed turbines between 1982 and 1984.[62] The number of developers has gradually decreased over time, with about two dozen now active at some level, and six--Cannon Energy, F1oWind, Kenetech-U.S. Windpower, New World

62 Williams and Porter, op. cit., footnote 6. Note that some estimates of the number of manufacturers and developers active at some level vary widely and are generally much higher. For example, some estimate that more than 50 manufacturing companies and 200 development companies were involved in wind development in the early 1980\. See Hamrin and Rader, op. cit., footnote 7, p. B-27.

Power, SeaWest, and Zond—accounting for about three-quarters of total installed wind capacity in the United States.[63]

The number of manufacturers has also decreased over time, with just one large U.S. manufacturer—Kenetech-U .S. Windpower—and several smaller manufacturers/project developers—including Zond, FloWind, Cannon Energy, and Advanced Wind Turbines—now producing or developing utility scale turbines.[64] Small standalone turbines are produced by firms such as Bergey Windpower, Northern Power Systems. and World Power Technologies.[bs]

Of all the wind turbines installed in the United States as of 1990, some 40 percent were imported.[66] The decline in the value of the dollar, however, is making it more difficult for European and Japanese firms to compete in the U.S. market.

Several large firms such as Boeing and General Electric participated in the early development of very large turbines (up to 4.5 MW) sponsored under DOE, but then left the industry as these turbines encountered significant technical problems, federal support was cut back, and energy prices dropped. Some large firms, such as Westinghouse, are now becoming active again in the wind industry, and considerable interest has been expressed by the aerospace industry. Kaiser Aerospace, for example, recently entered an agreement to manufacture turbines for Advanced Wind Turbines, Inc.

With increasingly competitive electricity markets and the shift toward competitive bidding (chapter 6), wind turbine manufacturers and developers require much greater capitalization and marketing depth/skill to survive. Many in the industry, such as Kenetech-U.S. Windpower, Zond, FloWind, and Cannon Energy, have responded by becoming increasingly vertically integrated, with the same firm manufacturing turbines, and developing and operating projects. Others. such as SeaWest and New World Power, have more extensively tapped outside sources of capital.

Research, Development, and Demonstration Needs

RD&D needs have been identified and discussed above, including ongoing wind resource assessment and improving the ability to forecast winds: improved materials for turbine blades: advanced airfoil design: improved towers; advanced computer models of wind turbine aerodynamics, particularly of wind turbulence and unsteady flows: and smart controls. The required expertise in basic materials and aerodynamic modeling is beyond the scope that is currently feasible by the wind industry.

The DOE wind R&D program is focused on joint ventures with industry to improve existing installations, develop advanced wind turbines, and upgrade the technology base through applid research. Initiatives include: the Advanced Wind Turbine (AWT) Program, a collaboration with utilities to evaluate state-of-the-art hardware and facilitate its deployment; the Utility Integration Program, which addresses concerns of grid integration; the Collaborative Wind Technology Program, which provides for cost-shared research with industry in the design, development, testing, and analysis of operational problems of current turbine technology; the Value Engineered Turbine Program, which focuses cost-shared efforts with industry on re-engineering or remanufacturing of conventional turbine configurations: and the Ap-

63 Randall Swisher, American Wind Energy Association, persona] communication, Aug. 25, 1994.

64 Others include Atlantic Orient, Wind Eagle, and Wind Harvest.

65 For a more complete listing of wind industry firms, see American Wind Energy Association, Membership *Directory* (Washington, DC: I 994).

66 Edward T.C. Ing, *Attorney* at Law, in letter *to* Deborah *Lamb,* Trade Counsel, Senate Committee on Finance, May 24, 1991. Note that this percentage has not significantly shifted since 1990.

TABLE 5-1: Examples of Cost-Effective Remote Applications of RETs

Agriculture
Pumping water for livestock or agriculture
Electric fences
Instrumentation

Rural homes or communities
Powering Ilihts, appliances, and communications equipment
Water heating system circulation pumps

Communications
Telephone systems, including cellular phones and emergency call boxes
Remote fiberoptic Installations
UHFA/HF radio and TV repeaters

Infrastructure
Parking lot and street lighting
Highway and railroad sign and signal lighting
Cathodic protection of e.g., bridges, pipelines
Navigational aids e.g., beacons, buoys, lighthouses, tower warning lights
Environmental monitors e g , meteorological, water level, and environmental quality

Transmission and distribution equipment for electric and gas utilities
Sectionalizing switches
End-of-feeder support
Dynamic thermal rating sensors
Pipeline flow meters and valve actuators
Medical and health care (remote medical clinics)
Refrigerators and freezers for vaccines and other medical supplies
Equipment for sterilizing medical Instruments
Improved lighting
Backup power and emergency communications

SOURCE Off Ice of Technology Assessment, 1995

plied Research Program, to develop the fundamental design tools for advanced wind turbines.

RENEWABLE ENERGY SYSTEMS

Three different renewable energy systems are examined here. These are systems for remote applications, utility applications where large-scale renewable energy plants are integrated into the grid, and distributed utility applications of small-scale RETs.

Remote Systems

Even relatively expensive renewable energy technologies can be cost-effective today in a variety of remote—at a distance from the existing electricity grid—applications (table 5-1). Their cost-effectiveness in particular applications is determined by the extent to which they reduce the use of fossil fuels that have to be hauled in at considerable expense or avoid the installation of costly transmission lines to provide power from the electricity grid.

These remote applications are a high-value use that is beginning to provide an important early market for RETs. Remote applications provide manufacturers a means to develop a distribution and maintenance infrastructure, important information about how best to design and market products for a particular area and application, and a network of contacts and loyalties. Similarly, remote applications provide users the opportunist y to test these technologies; train personnel; gain early technical, managerial, and operational experience; and build confidence in the technology. For example, remote app ications have been the primary market for developing the PV industry and have provided much valuable experience for both producers and users.

Improved understanding of the structure of the market for remote applications is very important in order to map an evolutionary path for the development of corresponding renewable technologies. For example, for a particular RET at a specific price: how large is the market and what are the key market opportunities; what factors determine the purchase of a particular RET (such as a PV lighting system); and what productivity gains and financial returns might be realized by using a particular RET (such as for agricultural water pumping)? Increased analytical effort is necessary for these factors to be adequately understood and an effective national strategy for remote applications—particularly in developing countries—to be developed. Given the limited resources of most renewable energy firms, public-private collaboration may offer a useful means of proceeding.

Remote applications require complete energy systems, which provide electric power (and energy services) when it is needed and in the form needed—at the specified voltage, current, and quality[67] of power required by the application. In contrast, many of the individual technologies described above, particularly the solar and wind RETs, provide alternating current (ac) or direct current (de) at some voltage-depending on the particular technology—when the resource is available. The form of power and the time when it is avai able may not match the application requirements.

Renewable energy systems typically consist of: 1) a RET to gather the energy resource and generate electricity; 2) a power conditioning unit to convert the electricity to the desired current (dc or ac), voltage, and quality needed for the application: 3) backup equipment (i.e., storage such as batteries or a generator such as a diesel engine[68]) to provide power when the renewable resource (such as wind or sun) is not available; and 4) control equipment to do all of this safely and efficiently.

The design and cost of these system components depend on the specific application. A PV water pumping system may need little or no backup while a PV lighting system may operate completely off battery storage.

Three primary considerations determine the relative size of the backup (storage or other) capacity: 1) the timing and size of the powerdemand (the load curve); 2) the availability-day-night, weather-related (cloudy or windy days), or seasonal-of the resource (intermittence); and 3) the acceptable risk of not having power (the reliability). These factors are interrelated.

Remote loads can be served either by extending transmission and distribution (T&D) lines from the existing electricity grid or by onsite generation.[69] Grid extension is a large fixed investment that is relatively insensitive to the load and that increases with distance .70 In contrast. the cost of re-

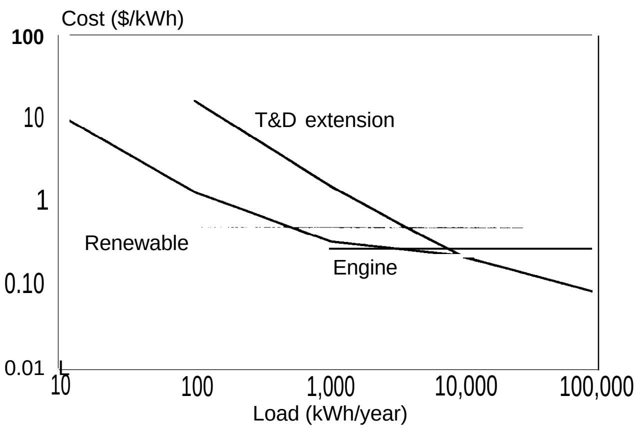
67 High-quality power has a nearly sinusoidal single-frequency (i.e., 60 Hz) waveform (with few harmonic frequencies); little variation in average voltage; no voltage spikes or switching transients (sudden changes in the voltage waveform due (o the switching of certain power electronic devices in the power conditioning unit); or other deviations. High-quality power is important to prevent damage to equipment; to prevent interference with communications, computer, or other equipment; and to ensure efficient operation.

68 Renewable systems coupled with conventional engine generators are usually called hybrid systems.

69 See, e.g., J.E. Bigger and E.C. Kern, Jr., '" Earl y, Cost- Effective Photovoltaic Appl i cations for Electric Utilities," paper presented at Soltech 90, Mar. 21, 1990, Austin, TX; and M. Mason, "Rural Electrification: A Review of World Bank and USAID Financed Projects," background paper for the World Bank, April 1990, p. 27.

70 Most of the cost in Putting the system into place is in the power poles, labor, right-of-way, and so forth. In a particular case, typically less than roughly 10 percent of the total cost is determined by the wire or the transformers-i. e., the load-carrying capability.

FIGURE 5-4A: Cost-Effectiveness of T&D Extension, Engine Generators, and PVs, by Electricity Load



NOTE: At a given distance from the utility grid, a RET such as PV is the lowest cost source of power at relatively low electricity demands, an engine may be the lowest cost generator at intermediate demands, and grid extension will be the lowest cost source of power at high demands. As PVs drop in price, they are cutting into the market for engine generators (the horizontal line for PVs shifts down), prompting some manufacturers of engine generators to develop RETs such as dish stirling in order to protect their market in the future. The calculation illustrated here assumes a 1-km line extension at a cost of $15,000 with 4-percent annual maintenance, a 30-year lifetime, a 10-percent cost of capital, and 7¢/kWh for electricity. The engine is assumed to cost $700/kW, 2¢/kWh for operations and maintenance (O&M), 15¢ to 23¢/kWh for fuel (depending on the size), and has a 66-percent capacity factor, a 10-year lifetime, and a 10-percent cost of capital. The PV system is assumed to have an installed cost of $10,000/kW, O&M costs of 5¢/kWh, and a capacity factor of 20 percent. Actual values in the field can vary considerably from those assumed here.

SOURCE: Office of Technology Assessment, 1995.

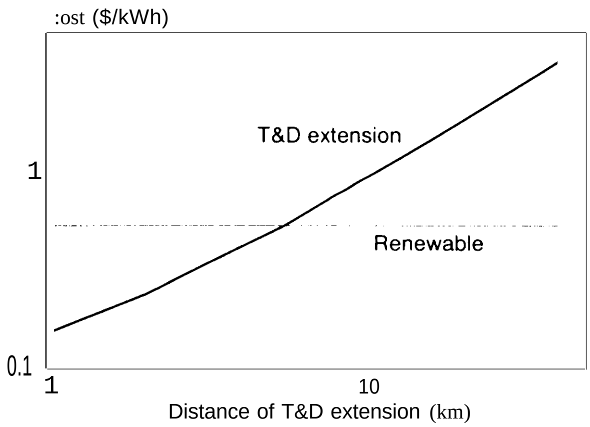
mote generation is little affected by distance from the grid and scales directly with the load. For a particular load, at some distance+ ailed the break-even distance—the cost of grid extension exceeds that of remote generation.

Onsite generation is most commonly done today by a small diesel or gasoline engine coupled to a generator. This technology has a relatively low initial cost, is widely available, can be installed anywhere, and uses a familiar technology. It is dependent on fossil fuel, however, which may be difficult and expensive to transport to the site. Consequently, for a range of conditions a particular RET will have lower total costs to generate electricity y.

In many cases, hybrids consisting of a RET and battery storage system backed up with an engine generator can be considered. This can reduce the need to oversize the RET and battery storage to handle extended periods without any renewable energy input, improves reliability, and reduces the high cost and unreliability of transporting large quantities of fuel to the site for a generator alone.

These alternatives-T&D extension or on-site generation by engines or renewable systems--can be compared in several ways, as shown generically in figure 5-4. The cost and performance tradeoff between these alternatives is determined by the load, the distance to the site, and a host of other factors. Estimation of the cost and performance of specific remote power projects must include site-

FIGURE 5-4B: Cost-Effectiveness of T&D Extension and PVs, by Length of Grid Extension



NOTE: At an intermediate level of power demand (20 MWh/year), corresponding to a village power system, extending the T&D grid will be most cost-effective over short distances (up to about 5 km), while PV-generated electricity will be most cost-effective at longer distances from the grid. The crossover point shown here is quite sensitive to the power demand. Lower power demands, for example, make the PV system cost-effective at distances closer to the grid. Parameters are the same as in figure A.

SOURCE: Office of Technology Assessment, 1995.

specific factors and current RET costs using one of the many computer packages or design handbooks available.[71] System reliability depends on the local renewable energy resources, the RET, and its backup, compared to the likelihood of T&D lines being downed, or to the reliability of both the engine generator and the fuel transportation infrastructure.

Industry

The PV industry relies almost exclusively on remote applications for its sales (chapter 7). Segments of the windpower industry, such as Bergey Windpower, Northern Power Systems, and World Power Technologies, also concentrate on remote markets and have numerous turbines in the field. Similarly, some solar thermal firms see remote applications as an important market opportunity and are specifically developing RETs for this market. An example is the 7-kW dish stirling system being developed by Cummins Power.

| Utility Systems

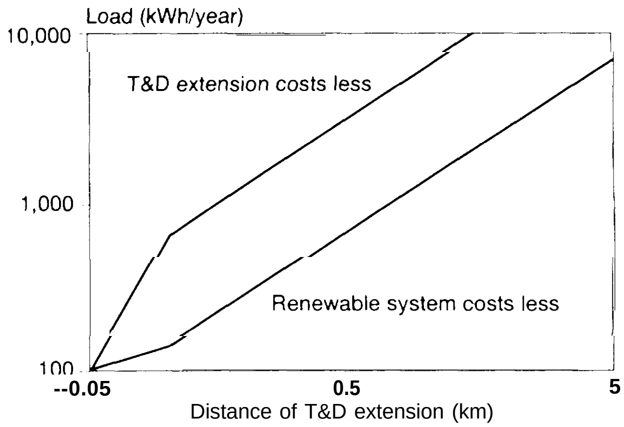
RETs have unique characteristics that present both problems and opportunities when integrated into an electricity grid. These include intermittence, power quality, site specificity, and modularity.

Intermittence

Use of intermittent renewable resources—such as solar and wind energy-offsets fuel use by conventional generating technologies. In addition, iRETs can reduce the need for conventional generating capacity. The factors that determine how much reduction is possible include:[72]

- *The match between the renewable resource and the local utility peak loads.* Good matches, such as PV or solar thermal matching summer air conditioning demands,[73] have higher capacity value.

FIGURE 5-4C: Cost-Effectiveness of T&D Extension Versus PV Systems as a Function of Power Load and Distance from the Utility Grid



NOTE At high levels of power demand and 'or relativelyshort distances from the utility grid, T&D grid extension can be the lowest cost option conversely at low levels of power demand and/or longer distances from the utility grid a stand-alone RET such as a PV system can be the lowest cost option The upper line assumes a high cost of grid extension ($1 5,000/km) and a low Installed cost foraPVsystem($6000/kW), the lower line assumes a low cost for grid extension ($7,500/km) and a high Installed cost for a PV system Parameters are the same as in figure A

SOURCE Off Ice of Technology Assessment 1995

71 See, e.g., Photovoltaic Design Assistance Center, *Stand-Alone Photovoltaic Systems: A Handbook of Recommended Design Practices*, SAND87-7023 (Albuquerque, NM: Sandia National Laboratories, November 1991). The National Renewable Energy Laboratory, Golden, CO, is also developing such tools.

72 See, e.g., Yih-huei Wan and Brian K. Parsons, *Factors Relevant to Utility Integration of Intermittent Renewable Technologies*, NREL/TP-463-4953 (Golden, CO: National Renewable Energy Laboratory, August 1993); Michael J. Grubb and Niels I. Meyer, "Wind Energy: Resources, Systems, and Regional Strategies, " in Johansson et al. (eds.), op. cit., footnote 3; Henry Ken y and Carl J. Weinberg, "Utility Strategies for Using Renewable," in Johansson et al. (eds.), op. cit., footnote 3; Adrianus Johannes Maria Van Wijk, Utrecht University, "Wind Energy and Electricity Production," 1990; and M.J.Grubb, "The Integration of Renewable Electricity Sources," *Energy Policy*, September 1991, pp. 670-688.

73 As structures and their surroundings tend to warmup over a period of time, peak air conditioning loads occur in the afternoon, generally after the peak solar resource, and also depend on the humidity.

PAUL GIPE

Zond, Inc. wind farm at Tehachapi, California, using wind turbines manufactured by Vestas of Denmark.

- *The level of iRET penetration into the grid.* High levels of penetration may tend to saturate their potential capacity value.
- *Geographic diversity.* Gathering renewable energy over a large area can moderate local fluctuations and increase capacity value.
- *The match between different renewable energy resources.* Wind and solar, for example, may complement each other in some areas and provide capacity value that individually they could not.

The extent to which an iRET can offset conventional capacity helps determine its economic attractiveness. Some utility planning models and policies, however, may not fully credit the iRET with potential capacity savings. Although further study of the capacity value of iRETs is needed, there are many cases today where a reasonably accurate value can be determined.

The variability of intermittent renewable may, in some cases, complicate utility operations by requiring greater cycling up and down of conventional generation equipment (load following) in order to meet demand. (See box 5-3 for a discussion of utility operations.) This may require operation of conventional equipment at lower (and less efficient) loads in some cases and may increase wear and tear. The same factors as above—the match with the load, penetration level, geographic diversity, use of complementary resources, and others-can all influence the amount of cycling necessary. Experience with wind farms in California has shown that the electric utility system can operate normally when 8 percent of the system demand is met by wind.[74] Further, some modeling suggests that intermittent could provide much higher fractions of utility capacity without causing difficulties.[75] Improved understanding of these factors will be very important.

The intermittence of wind and solar can be moderated or circumvented by using natural gas or other fuels or stored resources (such as hydropower, compressed air, and batteries) to provide backup power. Solar thermal parabolic trough plants in California, for example, use natural gas backup to provide dispatchable peaking power.[76] Other combinations include natural gas hybrids with biomass or geothermal, biomass cofired with coal, and wind coupled to compressed-air energy storage or pumped hydro. The feasibility and cost-effectiveness of these or other hybrids depends on the particular case.

At high levels of penetration, the intermittence of some RETs may complicate utility planning and operations, but it is a challenge that utilities are familiar with in form if not in degree. Utilities now deal with a variety of plants using different resources—such as coal, oil, gas, nuclear, hydro, and municipal solid waste—with varying availabilities—for example, from baseloaded nuclear to gas peaking. Utilities have well-developed procedures for ensuring system reliability and efficiency with the current wide mix of resources and generation technologies.

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74 Wan and Parsons, op. cit., footnote 72.

75 Kelly and Weinberg, op. cit., footnote 72.

76 The amount of natural gas that can be used is limited by Public Utility Regulatory Policies Act regulations.

Power Quality

Concerns have been raised that renewable energy equipment could disrupt the quality of power provided by the electricity grid. These problems have largely been overcome. For example. some older RETs, particularly wind turbines, used induction generators, resulting in large reactive power[77] that can create problems on the electricity grid if not adequately corrected.[78] The current generation of variable-speed wind turbines avoids this problem and can actually reduce the amount of reactive power on the grid.

Some RETs, particularly PVS and advanced variable-speed wind turbines, use electronic power conditioners to convert dc or variable frequcncy ac to 60 Hz ac power. Early generations of equipment to do this could cause unwanted harmonics, switching transients, or other power quality problems that could reduce efficiency, shorten lifetimes of equipment, or interfere with communications and computer equipment. Extensive experience at a number of sites in the United States and other countries has shown that well-designed equipment can avoid these problems.[79]

With a large penetration of RETs into the grid, particularly small distributed units, power flow could be reversed in some segments from the direction originally intended. This can potentially cause problems with equipment protection devices; these may need to be modified or replaced over time.

In some cases, RETs distributed throughout a electricity grid can continue to generate power even when the primary power from the central station is lost (such as when a power line is down).[80] This poses potential safety problems to utility workers trying to repair downed power lines that they do not expect to be energized (or raises costs if they have to work on live lines), and it poses potential equipment problems when the downed lines are reconnected.

Site *Specificity*

Renewable have mixed impacts on electricity transmission and distribution requirements due to their highly diverse nature. Renewable installations such as geothermal, biomass, solar thermal, and wind are often tens of megawatts to 100 MW or more in size and are often located at a distance from populated areas. To transport the power they generate to load centers may require a long transmission line extension just to reach an existing transmission line as well as upgrading the transmission system. Developing T&D systems for RETs can significantly raise overall costs. In contrast, although coal or nuclear plants may be located at a distance from their load center, they can often be located to minimize additional T&D costs.

Further, for iRETs such as wind or solar thermal, the T&D system will operate at a relatively low-capacity factor-carrying little power for extended periods when there is little wind or sunshine. but sized for the full rated power generated when winds or sunshine are strong. These low-capacity factors raise the relative T&D costs for these systems. In some cases, backup with other

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77 Reactive power, in this case, is caused by the creation and collapse of magnetic fields in the induction generator as It generates 60-cycle power.

78 Correction is readily done, for example, by using large banks of capacitors. There is a cost associated with this. however.

79 John J. Bzura, "Residential Photovoltaics," in *Photovoltaics: New Opportunities for Utilities*, DOE/CH 10[]93- 113 (Washington, DC: U.S. Department of Energy, July 1991).

80 In [he longer term, this may be a desirable characteristic as it could improve the reliability of providing power to customers in that area, even with the main power cut off.

generation systems or with energy storage systems[81] may be cost-effective in raising these low T&D capacity factors.

In contrast, small-scale renewable such as small wind, PVs, and dish stirling can be widely dispersed within the utility service area and may then be able to reduce peak loading on the T&D system, increasing reliability and reducing T&D investment and other costs (see below).

Reliability

Renewable may have mixed impacts on system reliability. The often smaller size of renewable generating units, such as biomass, geothermal, and wind, compared with conventional coal, nuclear, or other units, could increase reliability because loss of a small unit poses less of a threat to the system. Similarly, very small units distributed throughout the utility service area (see below) can potentially increase reliability. On the other hand, iRETs may, in some cases, increase cycling of conventional equipment and thus raise the likelihood of reliability problems, at least until these resources and their integration into the electricity grid are better understood and until automatic dispatch incorporating intermittent renewable is well developed.

The relatively small, modular size and rapid installation times for many RETs also means that capacity can be added as needed rather than in large lumps as with conventional powerplants. This can reduce the risk of building a large powerplant, beginning many years in advance, that may or may not be needed when the plant is completed. Advanced gas turbines and fuel cells, however, also provide the advantage of modular, relatively small units and are substantially eroding this advantage of renewable.

Distributed Utility Systems

In the conventional utility, power is generated at central locations and is transmitted to users through long-distance transmission lines, substations, and distribution lines. In recent years, utility systems have increasingly included smaller scale (10s of MWs) generation by nonutility generators.

The distributed utility (DU) concept[82] would take this trend substantially further, spreading very small generators (kWs to MWS) throughout the utility T&D system. In the DU, the central utility is still likely to provide a large share of the power as well as ensure overall system integrity. The distributed generation equipment will provide important supplemental and peaking power. Potential generators include PVS, dish stirling, wind systems, and other RETs at sites-depending on the technology—such as rooftops, local substations, and transmission rights-of-way. Engine generators or fuel cells, perhaps fueled with natural gas, may be strong competitors for these DU applications.

The DU concept is based on several simple, but important issues:

- T&D is a growing share of the total cost of utility systems due to increasing costs such as for rights-of-way and construction, and declining construction of baseload plants.
- T&D systems are often substantially underutilized most of the time, operating only briefly at high loads[83] (see figure 5-5). Sizing T&D systems to handle these brief periods of high demand is expensive. Locating small generators

81 A. J. Cavallo et al., Center for Energy and Environmental Studies, Princeton University, "Baseload Wind power from the Great Plains fOr Major Electricity Demand Centers," March 1994.

82 The distributed utility concept has been examined extensively in Electric Power Research Institute, National Renewable Energy Laboratory, and Pacific Gas and Electric, "Distributed Utility Valuation Project," August 1993; P.R. Barnes et al., *The Integration of Renewable Energy Sources in/o Electric Power Distribution Systems, 2 vols., ORNL-6775* (Oak Ridge, TN: Oak Ridge National Laboratory, June 1994); and Electric Power Research Institute, *Advancements in Integrating DMS and Distributed Generation and Storage into T&D Planning: Proceedings from the Third Annual Workshop,* EPRI TR-104255 (Palo Alto, CA: September 1994).

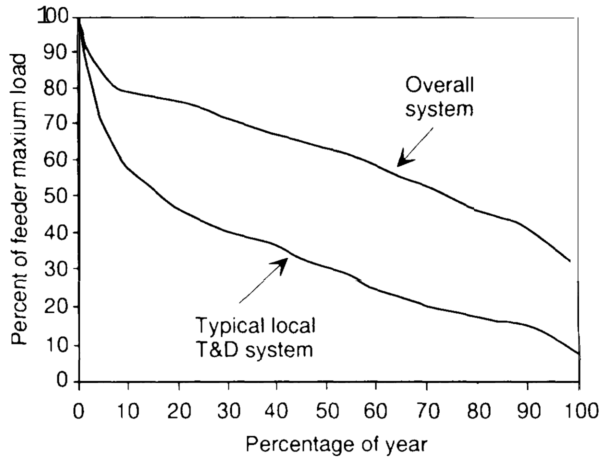
83 In part, this may be due to zoning regulations as they tend to concentrate similar loads—residential, commercial, industrial-in the same areas.

close to demand may reduce peak loads on the T&D system, improving capacity utilization. This is particularly important where peak loads are approaching T&D capacity limits. In this case, investment in local generation might cost-effectively allow a delay in upgrading the T&D system.

- Most (perhaps 95 percent) customer service problems-outages and power quality--occur not at the generating plant but in the distribution system. Distributed generation may reduce these problems with substantial economic benefit.[84]
- Environmental and other regulatory constraints, such as siting, are increasingly significant for conventional powerplants in some areas. These constraints may be less for many small, environmentally benign RETs.

For these and other reasons, interest is growing in the distributed utility as a potentially useful tool for improving overall utility cost and performance. Following analysis of the potential of distributed generation,[85] Pacific Gas and Electric (PG&E) installed a 500-kW PV plant near Fresno, California, as part of the PV for Utility Scale Applications (PVUSA) project. The plant was intended to generate energy, contribute capacity value, delay investment in substation equipment, and improve system reliability. Initial field data have confirmed a value of at least $2,900/kW of installed PV capacity.[86] Other utilities have calculated values for DU equipment ranging from less than $2,000/kW to more than $ 10,000/kW at various sites.[87] In comparison, a typical coal-fired central station powerplant has a capital cost of roughly $ 1,500/kW.[88] Thus, the value of distrib-

FIGURE 5-5: Capacity Utilization of a Typical Local T&D System



NOTE A typical local T&D system carries a high load for only very short periods of the year For example, the figure here shows that the local T&D system may carry a load 60 percent or more of its maximurn capacity for just 10 percent of the year corresponding to rare peak demands such as due to air conditionmg loads during summer heat waves In contrast, the overall generation system carries a much higher load throughout the year The low capacity factor of the local T&D system opens the opportunity of using distributed generation to meet the rare peak loads and thus reduce the investment necessary in the T&D system

SOURCE Joseph J Ianucci and Daniel S Shugar, "Structural Evoltion of Utlity Systems and Its Implications for Photovoltaic Applications, " paper presented at the 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, NV, 1991

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84 Narain G. Hingorani and Karl E, Stahlkopf, "High Power Electronics," *Scientific American,* November 1993, pp. 78-85; and A.P. Sanghvi, Electric Power Research Institute, "Cost-Benefit Analysis of Power System Reliability: Determination of Interruption Costs," Report EL-6791, 3 vols., April 1990.

85 D.S. Shugar, "Photovoltaics in the Utility Distribution System: The Evaluation of System and Distributed Benefits," paper presented at the 21st IEEE PV Specialists Conference, Kissimmee, FL, May 1990.

86 Preliminary data show a plant peak power availability of 82 percent, annual and peak load reductions in power output losses of 5 Percent and 8 percent, a four-year extension of transformer life, and a 12-year extension of transformer load tap changer life. Other potential benefits now being evaluated have a predicted value of an additional $3,000/kW. See Paul Maycock, "Kerman Grid Support Plant Provides Twice the Value of Central PV," *PV News*, vol. 13, No. 6, June 1994.

87 "Economic Evacuation of pV-Grid Support is Changing," *Solar Industry Journal,* 3rd quarter, 1994.

88 Note that this cost is not exactly Comparable as it does not include fuel costs and certain other factors.

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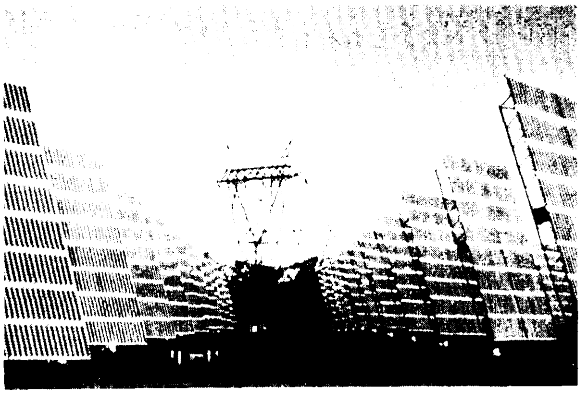

A grid-connected PV *powerplant* in California.

uted generation equipment can be much higher than that of central station powerplants. This creates a potential high-value market niche for technologies such as PVS that can be used in distributed generation applications.

PG&E and others have done subsequent analyses to identify promising areas for installing PVS for DU grid support, and the potential appears to be quite large.[89] For example, the Utility Photovoltaic Group estimated the market for distributed PV capacity at more than 8,000 MW at an installed price of $3,000/kW.[90]

Many questions remain, however, about how to plan, build, interconnect, and operate such a system while maintaining reliability and performance. Similarly, little is known about the range of conditions for which the DU might be economic, or how to find and evaluate such opportunities. Screening, planning, and evaluation tools need to be developed, particularly with sufficiently fine detail to capture the technical and financial benefits and costs of DU technologies on the local level while still providing a sufficiently broad scale to evaluate systemwide effects. Much technical development is also needed, such as hardware, software, and communications equipment for automating the DU. Field demonstrations are needed to validate these analyses and technologies.

It may also be possible to use intelligent controls to integrate PV or other RET power generation with the use of household appliances such as air conditioners and with the local electric utility. Some household appliances might be controlled by how much renewable energy was being supplied. If a passing cloud cut off PV output, certain appliances could also be shut down temporarily. Such devices could be easily integrated at low cost into adjustable-speed electronic drives now entering the household appliance market.[91] The development of standard protocols among appliance and other manufacturers is needed for such control systems to be developed and widely implemented. Such intelligent controls would also provide valuable demand-side management (DSM) capabilities to the local utility.

Recent work on the DU concept has been motivated, in part, out of interest in the potential of RETs. Space at urban substations is at a premium, however. RETs such as PVS maybe less practical at some of those sites than compact energy storage and generation systems—particularly if these systems are only operated for short periods during the year to reduce T&D system peak loading. Rooftop PV systems scattered throughout the area maybe desirable for high-penetration levels of DU systems.

OVERCOMING BARRIERS

The use of RETs for the generation of electricity is growing, but further action is needed to bring

89 Power distribution areas were examined, first to determine where there was a good match between the local load and the local solar resource and, second, to determine which of those areas are at or near their T&D capacity limits. These screens selected areas in PG&E's service territory with some 120 MW of load. Daniel S. Shugar et al., "Photovoltaic Grid Support: A New Screening Methodology," *Solar Today,* September/October 1993, pp. 2 I -24.

90 "DOE and Utilities," *NREL: PV Working with Industry,* fall 1994, p. 1.

91 Samuel F. Baldwin, "Energy -Efficient Electric Motor Drive Systems, "in Thomas B. Johansson et al. (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989).

RETs into widespread use and must be tailored for particular classes of RETs.[92] This section discusses ways to make RETs more cost-effective and to encourage their use.

Research, Development, and Demonstration Needs

Opportunities for RD&D in individual technologies as well as in remote, utility, or distributed utility systems are briefly sketched above. Overall, no insurmountable technical barriers have yet appeared that might prevent RETs from maturing into broadly competitive energy resources, but much RD&D remains to be done.

Federal RD&D funding for RETs has increased over the past several years, after a decade of declining and/or low budgets. Most of this support is focused on developing the technologies themselves and, in a few cases, improving associated manufacturing technologies. Additional support for high-priority RD&D of these technologies, balance of systems equipment, and manufacturing technologies could allow more rapid development.

Few utilities have been actively involved in the RD&D or commercialization of RETs.[93] The total RET R&D budget for the Electric Power Research Institute was just $9 million in 1993—2.8 percent of its budget.[94] EPRI did, however, provide important continuity in funding for RETs during the 1980s when the federal government cut back. More recently, pressure to generate near-term results has forced EPRI to reduce its longer term RD&D portfolio in areas such as PV.

Demonstration programs have often been one-of-a-kind and generally limited to very low-cost systems. Necessarily larger scale systems. such as integrated biomass gasification advanced gas turbine systems, solar thermal central receivers, and others have had a difficult time obtaining private or public support due to their size and cost. For example, development of advanced bioelectric systems might typically progress from the R&D phase to a $1 O-million pilot demonstration unit, to a $50-million engineering development unit, to a $200-million pioneer plant, followed by commercialization. The level of public support could be reduced at each stage, but would still be substantial even for the pioneer plant. However, such demonstrations are essential to eventual commercialization.

Private cofunding of such demonstrations is a key element to their eventual success. Utilities, however, may be discouraged by state regulators from trying new technologies as this could risk ratepayer funds. In response, some have proposed that a "safe harbor" be provided utilities that choose to experiment with and invest in RETs so that they can be assured of recovering their costs as long as they have acted responsibly. Currently, utilities face numerous risks—technical, financial, regulatory—in developing RETs. Even with the most careful management of a new technology program, the utility may face cost disallowances. Such risks may seriously constrain a utility's ability and willingness to try new technologies. Safe harbor rules would provide a mechanism to allow such experimentation.[95]

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92 Technologies that are relatively immature primarily require RD&D. Premature commercialization might fail to reduce costs sufficiently to attract a large market, and strand the technology at high costs with insufficient revenue to adequately support further development.

93 Detailed reviews of difficulties in considering renewables within the utility framework are provided by National Association of Regulator-y Utility Commissioners, Committee on Energy Conservation, Subcommittee on Renewable Energy. "Renewable Energy and Utility Regulation," April 10, 199 1; and Hamrin and Rader, op. cit., footnote 7.

94 Electric Power Research Institute, "Research, Development & Delivery plan 1993- 1997," January 1993.

95 David Moskovitz, "Renewable Energy: Barriers and Opportunities; Walls and Bridges," paper prepared fOr the World Resources Institute, July 1992.

Increasingly competitive electricity markets, particularly the possibility of retail wheeling,[96] may make such alternatives as safe harbors more difficult to develop (see chapter 6). For example, some argue that ratepayer-funded RD&D may be anticompetitive because it may strengthen utilities vis-a-vis independent power producers that have no such access to ratepayer funds.[97] Independent power producers, however, are investing very little in RD&D. Electricity sector restructuring also appears to be significantly reducing RD&D. The California Energy Commission, for example, estimates that RD&D in advanced-generation technologies by California Investor Owned Utilities will decline 88 percent in 1995, compared with 1993; overall RD&D will decline by 32 percent compared with 1992.[98] Alternative RD&D funding mechanisms may therefore be needed to ensure the long-term technological vitality of the electricity sector.

Regardless of how they are supported, demonstrations of these technologies are very important. Relative to conventional technologies, data on cost and performance, experience, and siting of RETs is not adequate. For example, there are no commercial-size, advanced biomass gasification pkmts on which utility executives can "kick the tires. " They are not necessarily biased against these technologies, they simply have no experience.

R&D is also needed on full-fuel-cycle energy efficiencies and environmental impacts for various conventional and renewable technologies (see chapter 6). Some of this has been done[99] and could be usefully extended.

Manufacturing Scaleup

A key challenge to large-scale RET production and use is needing a large market to scaleup production and thus lower costs, but needing low costs to develop a large market. Manufacturing scaleup and the resulting economies of scale and learning have been widely observed to reduce the cost of new technologies.] W

Several recent analyses of PV production for various periods between 1965 and 1992, for ex-

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96 Retail wheeling is the theoretical process of allowing individuals the opportunity to purchase their electricity frOm particular utilities or independent power producers, thus allowing them to shop around for the lowest price or for other features that they value. This is often crudely characterized as similar to the individual customer's ability to shop around for a long-distance telecommunications company. In fact, retail wheeling of electricity is not well defined and cannot be described by so simple an analogy. For a discussion of these issues, see, e.g., *The Electricity Journal,* April 1994, entire issue; Richard J. Rudden and Robert Hornich, "Electric Utilities in the Future, " *Fortnightly,* May 1, 1994, pp. 21 -25; and Public Utilities Commission of the State of Cal ifomia, *Order Instituting Rulemaking and Order Instituting Investigation* (San Francisco, CA: Apr. 20, 1994).

97 See, e.g., Public Utilities Commission of the State of California, Division of Ratepayer Advocates, "Report on Research, Development, and Demonstration for Southern California Edison Company General Rate Case," Application No. 93-12-025, March 1994, pp. 3-3 to 3-4.

98 California Energy Commission, *Restructuring and the Future of Electricity RD&D,* Docket No. 94-EDR-1 (Sacramento, CA: Jan. 31, 1 995).

99 See, e.g., Marc Chupka and David Howarth, *Renewable Electric* Generation: *An Assessment of Air Pollution Prevention Potential,* EPA/400/R-92' 005 (Washington, DC: U.S. Environmental Protection Agency, March 1992).

100 See, e.g., Ernst R. Berndt, The *Practice of Econometrics: classic and Contemporary* (Reading. MA: Addison-Wesley publishing Co., 199 I); and Linda Argote and Dennis Epple, "Learning Curves in Manufacturing," *Science, vol.* 247, Feb. 23, 1990, pp. 920-924. Indeed, failure to realize expected economies of scale and learning in new coal and nuclear plants during the past several decades has been a significant source of difficulty for the electric utility industry. P.L. Joskow and N.L. Rose, "The Effects of Technological Change, Experience, and Environmental Regulation on the Construction Cost of Coal-Burning Generating Units," *Rand Journal of Economic. i, vol. 16, No. 1,* spring 1985, pp. 1 *-27;* George S. Day and David B. Montgomery, "Diagnosing the Experience Curve," *Journal of Marketing, vol. 47,* spring 1983, pp. 44-58; and Martin B. Zimmerman, "Learning Effects and the Commercialization of New Energy Technologies: The Case of Nuclear Power," *The Bell Journal of Economics, vol. 13, No. 2,* autumn 1982, pp. *297-310.*

ample, found that every cumulative doubling of production reduced real costs to roughly 80 percent of the previous value.[101] This effect could have a significant impact on PV markets. For example, if projected business-as-usual PV market growth rates of about 15 percent were realized, the global PV market would be about 1 GW/year in 2010, [f the 80 percent progress ratio continued over this period. the cost of PV-generated electricity would then be about 10¢kWh. In contrast. if the market were to grow at an accelerated rate of 35 percent per year, the global market in 2010 would be 18 GW and, with the same 80 percent progress ratio, the cost of PV electricity y would be 6.5¢/kWh. By one estimate, the additional cost of such an accelerated development strategy would be about $5.4 billion (1992 dollars) for additional RD&D and market support.[102] Other estimates range from $5 billion to $9 billion (see above). Such a strategy might have significant environmental, international competitiveness (see chapter 7), and other benefits.

Simply producing more PVs, however, will not necessarily lower costs at an 80 percent progress ratio. RD&D in technologies, systems, and manufacturing to achieve such cost reductions would be fundamental to any accelerated development strategy.

The PV Manufacturing Technology Project, a joint venture between DOE and industry, is intended to reduce PV manufacturing costs. DOE support for PV manufacturing improvements is $19 million in fiscal year 1995.

Resource Assessment

Renewable resources have several defining characteristics, including site specificity, intermittence, and intensity. These factors. their implications, and strategies for dealing with them are discussed above and in chapter.[103]

Although resource data are being developed. additional efforts could provide valuable information for potential users. Of particular interest is more detailed information on site-specific resources, geographic variation for individual resources. and regional correlations between resources. Further development and dissemination of analytical tools that can make effective use of this data may also be of great interest to those considering using RETs, particularly for determining the capacity value of iRET resources, and the impacts of iRETs on utility system operations and on T&D requirements. Analytical tools for forecasting renewable resources are also needed.

Commercialization

Several strategies for helping develop markets in parallel with manufacturing scaleup were listed in chapter 1, including developing market niches, aggregating purchases across many potential customers, and more aggressively pursuing international markets (chapter 7). One perspective of the market opportunities for PVs is shown in tigure 5-6, developing gradually from remote systems, to grid support, peaking, and finally bulk power. Market development paths for other RETs could differ.

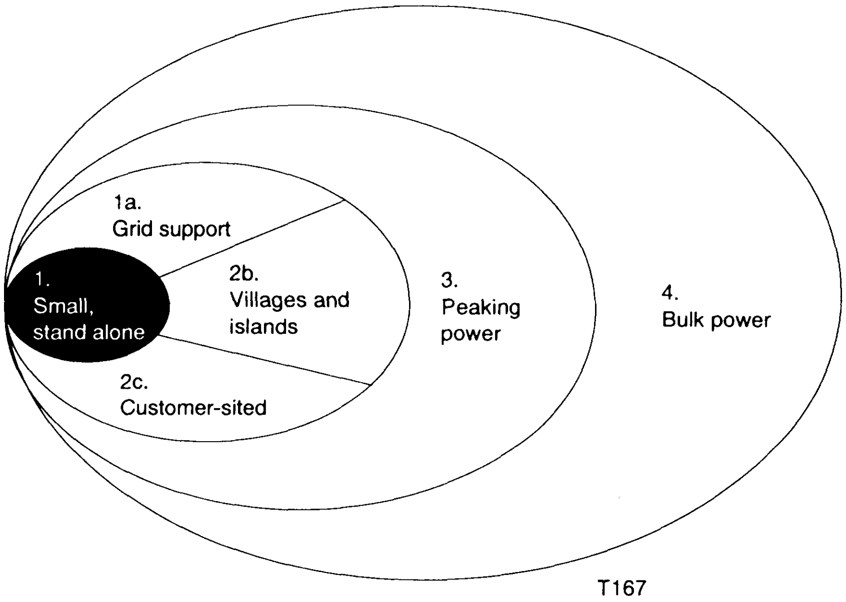
Remote markets are of particular near- and mid-term importance for several RETs, including small wind systems, PVs, and small solar thermal powerplants. Developing these markets offers the opportunist y for substantial scale up in manufacturing volume and thus will significantly influence the evolution of these technologies. Additional research is needed to better understand the remote power market, including specific applications,

[101] The values of this progress ratio were 80, 81, and 81.6 percent, depending on the period examined. See Richards, op. cit., footnote 50; Cody and Tiedje, op. cit., footnote 49; and Williams and Terzian, op. cit., footnote 49.

[102] Williams and Terzian, op. cit.. footnote 49.

[103] For example site specificity requires extensive long-term resource evaluation and the development of appropriate analytical tools such as geographic information systems. Intermittence} can be addressed by collecting the energy over a larger geographic area, combining the resource with other complementary resources, or forming hybrids with other generation technologies (e.g., fossil, hydro, biomass) and or storage.

FIGURE 5-6: Market Evolution Model for PVs



NOTE: One model for the market evolution of the PV industry is a gradual movement from high-value stand-alone projects to somewhat lower value grid support, and village-size systems, to medium-value peak power applications, and ultimately to bulk power. The potential production volume grows rapidly as these new markets open up.

SOURCE: Joseph J. Ianucci and Daniel S. Shugar, "Structural Evolution of Utility Systems and Its Implications for Photovoltaic Applications," paper presented at the 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, NV, 1991.

their number and value, and how to best develop them.

Grid support (distributed utility) also offers a substantial near- to mid-term opportunity, but remains poorly understood. Better analytical tools are needed that can screen for such opportunities, and more detailed analysis is needed to determine the full value of these applications. RETs such as PVs are likely to face significant competition for these grid support markets from fuel cells, diesel engines, and other fossil-fueled technologies.

Peaking and bulk power represent huge markets, but are also more competitive. Fossil power technologies are advancing and will remain strong competitors (box 5-1). To be competitive, RETs may need to be appropriately credited for their actual capacity value, environmental benefits, ability to lower fuel cost risks, and other advantages, as well as charged for their disadvantages compared with fossil fuels. Electricity sector planning models currently in use may not be easily adaptable to these or other aspects of RETs, such as their often small capacity increments or T&D requirements. Case-by-case inclusion of these considerations for RETs in the planning process may carry high overhead; better analytical tools are needed to allow consideration of these factors with minimal cost and effort.

Many of DOE's market conditioning initiatives are implemented through joint venture project activities. Joint ventures, as well as project activities with decision makers and organizations representing PV target market sectors, are the major focus for translating RD&D activities into market impact. Through its joint venture activities, DOE has demonstrated willingness to share risk with those that invest in current technology at present-day prices while committing to high-volume, lower cost product purchase in the future. Developing relationships with stakeholders in this way is anticipated to lead to significant cost reductions while strengthening the market base for suppliers.

In 1992, the Electric Power Research Institute, the American Public Power Association, the Edison Electric Institute, the National Rural Electric Cooperative Association, and approximately 40 utilities formed the Utility Photovoltaic Group (UPVG) to promote early commercialization of photovoltaics. In September 1992, DOE agreed to provide up to $800,000 for the first 18 months of UPVG's activities. UPVG and DOE have started TEAM-UP (Technology Experience To Accelerate Markets in Utility Photovoltaics), a $500-million (two-thirds privately financed) joint venture to purchase 50 MW of PV over six years.

The PVUSA project is a field test of large PV installations intended to demonstrate the viability of PV systems in a utility setting. PV-BONUS is a DOE program that was recently funded as a public-private effort to develop cost-effective PV products, applications, and product-supply and product-user relationships in the buildings sector. This sector is expected to be another steppingstone to the bulk power market and holds promise of becoming a substantial market in its own right. Phase I is a concept development stage, requiring a minimum 30-percent cost share by the private participant, and up to $1 million is expected to be provided for preliminary market assessment and product development tasks and evaluation in this phase. Phase II will include product development and testing, and Phase III will be field demonstration and performance verification. Overall program funding will require 50-percent cost-sharing by private participants. Total DOE support for market conditioning activities is $35 million in fiscal year 1995.

Many people, including policy makers at the state and federal level, are unaware of how rapidly the performance and cost-effectiveness of many RETs are improving, the magnitude of the locally

Solar thermal-natural gas hybrid electricity-generating system in the Mojave desert, California.

available renewable resources, or the practical aspects of system design, integration, and finance. For rapidly advancing technologies such as wind or PV, data two or three years out of date may be of little value. The lack of information has been a particularly serious problem at the state regulatory level where the embryonic renewable energy industry has not had the resources to present its case. Most public utility commission staffs tend to be small and have often not been able to collect and keep current the necessary information.[104] Equally important is providing a credible independent source of information to balance the excessive claims of some renewable energy advocates. The decline in federal support for renewable energy during the 1980s reduced the dissemination of relevant information in an appropriate format.

Initiatives to support RET commercialization must take into account change occurring in the electricity sector (see chapter 6). Restructuring and greater competition may entail unbundling of services, thereby opening a variety of market niches such as grid support. On the other hand, separation of generation from transmission and

104 National Association of Regulatory Utility Commissioners, Committee on Energy Conservation, Subcommittee on Renewable Energy, *Renewable Energy and Utility Regulation* (Washington, DC: Apr. 10, 1991).

distribution may impede identification and use of such distributed applications. The net effects of these opposing forces are unclear.

POLICY OPTIONS

Support for the technical development of RETS in the electricity sector has been provided for some two decades and has contributed significantly to the dramatic improvements in the cost and performance of many RETs over this period.

Federal RD&D in RETs has increased in recent years (see table 1-4 and figure 2 in appendix l-A) after declining in the 1980s. The focus of present RD&D efforts is primarily mid- to longer term RD&D, with some support for public-private, cost-shared commercialization activities. This will allow more rapid technical development of RETs than would occur without federal support, but RET contribution to U.S. electricity supplies (now about 11 percent, mostly from hydropower) is likely to remain a relatively small proportion of the total over the next 15 years. During this period, however, this support will help provide the technical foundation for more rapid expansion of RETs after 2010. Total nonhydro RET electricity generation is projected by the Energy Information Administration (EIA) to increase from about 46 billion kWh in 1993 to 112 billion kWh in 2010.[105] Such estimates are highly uncertain, however, and could be far too optimistic or pessimistic depending on the public policies chosen in the next few years. For example, a focused public-private effort to develop bioenergy crops in order to offset farm supports could encourage the development of perhaps two to three times as much generation capacity as is currently projected by EIA for 2010.

Reductions in RD&D supports for RETs could save some federal outlays in the near term, but are likely to significantly reduce the rate of development of these technologies. As noted above, the RET industry is too small to support this level of RD&D itself, and many potential outside partners are reducing their RD&D investments, particularly for longer term, higher risk technologies such as many renewable. Slowing these programs significantly risks both losing important international markets to foreign competitors and the sale of innovative U.S. RET firms and technologies to these foreign concerns. If RD&D supports must be reduced, it will be important to protect core RD&D activities including public-private partnerships to demonstrate technologies.

Strategies that would allow additional cost-effective applications of RETs to be captured sooner are outlined below. Adoption of such strategies could help strengthen U.S. manufacturers in international markets (chapter 7), allow a more rapid transition to nonfossil forms of energy should global warming or other factors make this necessary, and diversify energy supplies and reduce exposure to the risk of any future fuel cost increases (chapter 6). However, these strategies would require greater federal outlays, depending on the particular policies pursued. Many of these activities are relatively low cost and have potentially high leverage. These include resource assessment, much R&D, the development of design tools and information programs, and standards. Demonstration programs are generally higher cost, but should be leveraged—as should many other activities—with public-private partnerships. The activities discussed below, for which DOE would have prime responsibility at the federal level, are likely to be particularly effective: whatever strategy or budget level is selected, ensuring the maximum contribution from RETs in the future will depend on choosing policies with the greatest leverage.

Resource Assessment

- Renewable resource assessment and the development of appropriate analytical tools is essential for potential users to identify attractive

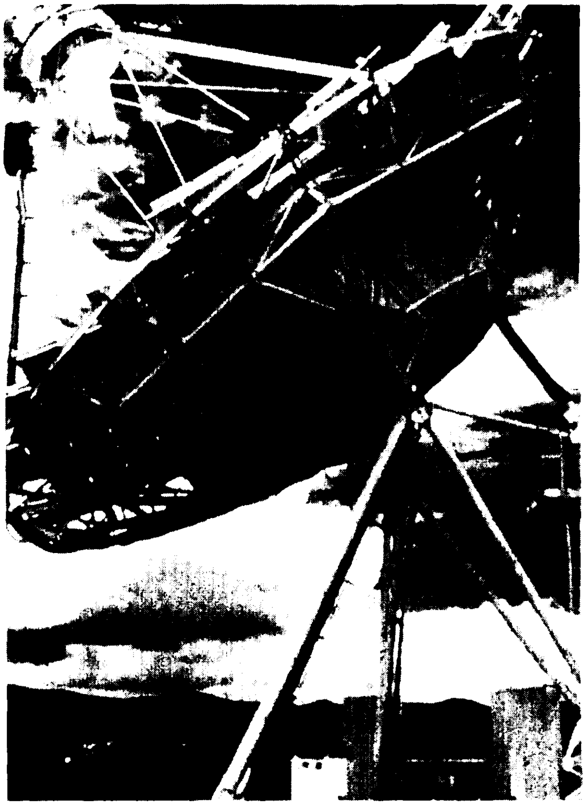
105 U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook, 1995,* DOE/EIA-0383(95) (Washington, DC: January 1995).

opportunities. The FY 1995 appropriation for solar resource activities is $3.95 million—up from the FY 1994 level of $2.2 million. This increase in funding will allow an expansion of the resource monitoring network, the development of a more comprehensive database, and support data integration and geographic analysis.

- Additional monitoring sites could improve understanding of how large the resources are, how they vary at specific sites and between different sites, and to what extent different resources—such as sun and wind—may be complementary.[106] In turn, this data and appropriate analytical tools might be used to determine iRET capacity values, improve utility planning and operations with iRETs, and provide other benefits.

Research, Development, and Demonstration Programs

- *R&D.* Overall program budgets for RD&D are listed by RET in table 1-4. These supports have increased from the low in 1990 of$119 million to a FY 1995 level of about $331 million. '07 (Half of this increase occurred in 1991 and 1992 following the Bush Administration's development of the National Energy Strategy.) When this funding is spread across the full range of RETs, however, these programs continue to be substantially constrained. Support for high-leverage R&D opportunities could be directed to particular RET technologies, balance of system components, hybrid systems, system integration, and RET manufacturing technologies, as discussed above.
- *Demonstraticns.* Demonstrations of larger scale systems, particularly bioenergy, geothermal, and solar thermal central receiver systems, have not been possible even though they would have been smaller than many fossil fuel systems that have been funded in recent years.



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A parabolic dish stirling engine system under test. A variety of dish stirling designs have been developed and tested and a joint DOE-Cummins Power Generation venture is in the final stages of developing a 7.5 kW system for commercialization.

Such demonstrations have been and must continue to be driven by private sector interest in commercializing these technologies, but federal involvement maybe necessary to get projects under way.

- Safe *harbors.* While the federal government does not have direct authority to create safe harbors for utility or independent power producer RD&D, it could encourage states to provide them, provide useful information, or perhaps provide seed money or tax considerations for doing so. Consideration might also be given to other mechanisms to encourage private sector

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106 That is, t. what extent one resource increases when the other decreases, thus compensating in part for each others' natural variability.

107 This overall funding level also includes Some support for solar building and other activities. Note that a number of activities listed in the DOE Solar and Renewable Energy budget are not specifically related to renewable energy and are not included in these budget numbers here.

RD&D in electricity sector technologies, such as sectorwide kWh or emissions taxes to support RD&D and focused tax credits.

Design, Planning, and Information Programs

- *Design and planning tools.* Support, leveraged with private sector funds, might be provided for the development of electricity sector design and planning tools that adequately incorporate consideration of renewable resource availabilities, RET capacity factors, T&D requirements, distributed utility benefits, environmental benefits, fuel cost risk reductions, and other factors.[108] This includes geographic information systems that enable long-term planning of energy infrastructure—such as T&D systems or gas pipelines—to consider potential future siting of RETs so as to minimize costs of future infrastructure access. These tools would be of considerable value to utilities, non utility generators, public utility commissions, federal policymakers, and others.
- *Information.* Support could be provided for information programs to develop data, particularly from field studies, and to put it into an appropriate format for use by policy makers and others at both the state and federal level. As noted above, this can encourage use of rapidly advancing RETs as well as check the excessive claims of some RET advocates.

Standards Programs

- Support might be provided for the development of technical standards for some equipment. This might include helping to support the establishment of control and communications protocols for use in home and office appliances and equipment that will allow smart controls to adjust appliance power demand as needed by utility demand-side management or distributed utility programs.

Finance and Commercialization Programs

- *Market aggregation.* Public-private partnerships can increase market volume so that manufacturers can scale up production processes. Several initial efforts of this type have been launched, such as the Utility Photovoltaic Group. More importantly, a longer term technology development, manufacturing scaleup, and market development strategy is needed, perhaps along the lines of what has become known as "Sustained Orderly Development.''[109] This would help provide manufacturers the assurance that there would be markets for them to compete for in the future, and would help them attract capital and scaleup manufacturing facilities in order to capture economies of scale and learning. If such a program is begun in the near term, additional RETs will be ready for large-scale commercialization as the large number of aging U.S. powerplants retire over the next decade or more.
- *Market analysis and development.* Overseas markets for RETs are potentially large, but are not yet well understood or developed. Support to analyze these markets and to develop them through trade missions, trade shows, resource assessments, technology demonstrations, and technical assistance could enhance exports and U.S. production.
- *Power marketing authorities.* The federal government could direct the Power Marketing Ad-

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108 Relatively little has been done in this area. DOE recently supported, however, the development of such tools for policy-level analysis. See, e.g., U.S. Department of Energy reports: Panel on Evaluation of Renewable Energy Models, Office of Utility Technologies, "Evacuation of Tools for Renewable Energy Policy Analysis: The Ten Federal Region Model," and "Evaluation of Tools for Renewable Energy Policy Analysis: The Renewable Energy Penetration Model," April 1994.

109 See, e.g., Donald W. Aitken, "Sustained Orderly Development," *Solar Today*, May/June 1992, pp. 20-22.

ministrations to develop all cost-effective RETs where practicable.[110]

- *Federal procurement. The* federal government could more vigorously pursue its mandate to use cost-effective RETs where practicable..[111]

CROSSCUTTING ISSUES

The importance of electricity throughout the U.S. economy opens numerous opportunities for cross-sectoral benefits from the use of RETs. For example, RET electricity could provide an early and important high-value market for bioenergy produced by the agriculture and forestry sector, be integrated with building demand-side management programs. be integrated with building structures, power electric transport, or provide an important niche market for fuel cells to be later used in the transport sector. Smart controls within buildings and within electric-vehicle recharging stations might allow much better integration of intermittent RETs into the electricity grid. These opportunities may offer important high-value market niches for earl y use of RETs that can help leverage manufacturing scaleup and cost reductions.

CONCLUSION

The development and integration of renewable energy technologies into the electricity grid poses a variety of technical, economic, planning, operational, and institutional challenges. Many of the technical challenges are being overcome, but much work remains. The cost-effectiveness of these systems varies widely. Some technologies are competitive in bulk power markets today: others are competitive only within higher value niche markets (without crediting their environmental or fuel diversity benefits). Costs are highly site- and resource-specific and must be evaluated on a case-by-case basis. Improved models and methodologies for evaluating the cost-effectiveness of these technologies would facilitate this evaluation and provide better decision making tools for determining the best use of RETs in the electricity sector. Development of these technologies will also play an important role in international markets. in which competition is becoming increasingly intense, as countries around the world have begun to focus on RETs as a key market for the 2 1st century.

[110] Including, e.g., environment], fuel diversity, and other costs and benefits.

[111] For example under the Department of Defense PV Implementation program formed in 1985 some 21,000 cost-effective applicati On\ Of PVS were identified in [he Navy alone which, if fully implemented, would provide net annual savings of about $175 million. The majority of these have reportedly not yet been implemented, with some 3,000 systems installed to date. See, e.g., Sandia National Laboratories, *Photovolta - ics for Military Applications: A Decisions-Maker's Guide,* SAND 87-7016 (Albuquerque, NM: May 1988); Sandia National Laboratory, *Photovoltaics Systems for Government Agencies*, SAND 88-3149 (Albuquerque, NM: May 1989); and John Ryan and Richard Sellers, "Overcoming Institutional Barriers."' *Solar Today*, March April 1992, pp. 18-20.