CHAPTER 6
RENEWABLE ENERGY[1]

...under "Sustained Growth"... [u]se of fossil fuels increases steadily over the next 30 years, fueling the economic development of a majority of the world population. By 2020-2030, they reach their maximum potential and no longer contribute to growth, being limited by the rate of production and commercialization of resources economically competitive with renewable energies. At that time a number of developing countries...increasingly turn their attention towards renewable energy sources...In this scenario, the rate of market penetration for identified renewable technologies – wind, biomass, photovoltaics – is similar to that of coal or oil and gas in the past."

Shell International Petroleum Company[2]

Renewable energy technologies (RETs) have made remarkable progress over the past two decades. Prices for energy from RETs such as wind turbines and photovoltaics (PVs) have come down by as much as 10 times.[3] Prospects for bringing RETs to broad market competitiveness are good. With continuing R&D coupled to carefully targeted demonstration and commercialization, RETs are now poised to become major contributors to U.S. and global energy needs over the next several decades. The Shell International Petroleum Company, for example, projects that by 2025 renewable energy sources could contribute to global energy one-half to two-thirds as much as fossil fuels do at present, with new renewable sources (excluding hydropower and traditional biomass) accounting for one-third to one-half of total renewables.[4] Likewise the Intergovernmental Panel on Climate Change (IPCC), in its 1995 assessment of energy supply options for mitigating climate change, estimated that renewables could contribute by 2025 about two-fifths as much energy as fossil fuels do at present.[5]

[1] More detailed references for Chapter 6 are provided in Appendix F.
[2] Shell (1995).
[3] For example, the price of wind-generated electricity has dropped from as much as \$0.80/kWh in the early 1980s to the range of \$0.04/kWh to \$0.05/kWh today, depending on the financing terms. The cost of PV modules has dropped from about \$50,000 per kW of capacity in the mid-1970s to around \$4000/kW today. See OTA (1995).
[4] Kassler (1994), Shell (1995).
[5] IPCC (1996).

MOTIVATION AND CONTEXT

RETs can contribute broadly to energy needs—electricity, fuels for transport, heat and light for buildings, power and process heat for industry—while addressing national challenges. Properly managed, these technologies generally have very little environmental impact, with little or no emissions of GHG or air pollutants, water contaminants, or solid wastes. Through the use of these technologies, the risk of global warming, the most difficult environmental challenge, is reduced, many of the regulatory controls on air emissions that are in place today become irrelevant, and health is improved. The inherent cleanliness of these technologies minimizes decommissioning costs and virtually eliminates long-term liability for possible environmental or health damages. RETs can also offset imports of foreign oil and offer important direct economic benefits.

Renewable energy resources include biomass,[6] geothermal energy,[7] hydropower,[8] ocean energy,[9] solar energy,[10] and wind energy.[11] Each of these has unique characteristics that require different approaches to R&D and system integration.

Resource and Technology Characteristics

Renewable energy resources have several important characteristics:

- Site specificity. Most of these resources vary by region and site—for example, how strong the sun shines or the wind blows varies from place to place; at most locations, however, there are one or more high-quality resources available. Ascertaining the optimal mix requires careful regional and site-specific evaluations of the resources over long periods; some degree of matching the system to the site; and, in some cases, relatively long-distance transport or transmission of the energy generated at the best resource sites to where people want to use it.

- Variable availability. Renewable energy resources vary in their availability—geothermal and biomass energy are available on demand; solar energy varies with the time of day and degree of cloud cover. Thus careful integration of intermittent resources like the sun and wind with other energy supplies or energy storage is needed to provide power when people need it.

- Diffuse energy flow. Most of these resources are diffuse, requiring large areas for energy collection, and concentration or upgrading to provide useful energy services. This increases up-front capital costs and encourages strategies to control costs, for example, by integrating systems into building roofs, walls, or windows. The diffuseness of the resource often leads to energy conversion at capacities much smaller than for conventional energy and to modular

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[6] Biomass includes the full range of organic plant materials, such as trees, grasses, and even aquatic plants. It can be burned to produce electricity and/or heat, or converted into liquid or gaseous fuels.
[7] Geothermal energy is the accessible thermal energy or heat content of the Earth's crust. It can be used to produce electricity, process heat, or to heat/cool buildings. Geothermal resources can be depleted locally.
[8] Hydropower is the energy drawn from water falling or flowing downhill.
[9] Ocean energy resources include heat-to-work conversion processes utilizing the temperature difference between surface and deep waters, recovery of potential energy from the rise and fall of the tides, and the recovery of kinetic energy from wave motion.
[10] Solar energy or sunlight is used to generate electricity directly using photovoltaic cells or to produce heat that can then be used directly or converted into electricity in a thermal power plant.
[11] Wind energy is used to turn a wind turbine to generate electricity; it is also used directly to power equipment such as water pumps.

system designs.[12] While such systems are not well suited for exploiting economies of scale in capacity, they are well-suited for factory mass production, which allows rapid reduction in costs with cumulative production experience; moreover, for such modular technologies a rapid rate of incremental improvement is more easily achieved as experience grows than with large-scale technologies.

- Low/no fuel costs.[13] Many RETs involve collecting natural flows of energy. Once the capital investment in the collection system is made, there are no recurring fuel costs. In effect, these systems pay upfront for energy collected over the lifetime of the system. This eliminates the risk of fuel cost increases but raises the upfront capital cost and risk if the system does not perform as predicted.

The technologies that tap renewable energy resources are similarly diverse. Biomass power technologies collect organic plant material—agricultural or forest product residues or dedicated energy crops—and burn it in systems similar to coal-fired power plants but smaller in scale. Conventional geothermal power systems use naturally trapped underground hot water[14] to power their generators; their biggest challenge is identifying and tapping hydrothermal resources, similar in many respects to oil and gas exploration and production. Photovoltaic devices consist of thin layers of semiconductors that generate electricity when sunlight hits them; they use many of the technologies of the electronics industry, but also can employ different, sometimes complex materials.[15] Solar thermal-electric systems concentrate sunlight to produce electricity in a thermal power plant; advanced systems face serious materials constraints due to the high-temperatures and thermal cycling.[16] Advanced wind energy technologies convert the kinetic energy in wind flows using three-dimensional aerodynamic principles to optimize energy capture by the turbine blades. Biomass fuels can be produced by genetically engineering enzymes to convert plant fiber (cellulose) into sugars and then ferment the sugars into ethanol. These diverse technologies that make use of leading-edge science and engineering.

System Integration Issues

Achieving major contributions from RETs in the energy economy will require addressing system integration challenges with new management strategies for thermal generating capacity, new uses for control technologies to ensure reliable, high-quality electric service, and new energy-storage technologies or strategies.

The extent to which intermittent RETs (iRETs), wind and solar, can penetrate utility grids without storage depends on what other generating capacity is on the system. An electric system optimized to accommodate iRETs would have less baseload and more load-following or peaking capacity.[17] (Thus the emphasis currently given to gas turbines and combined cycles in power markets will ultimately make possible greater roles for iRETs on electric grids without storage than if emphasis were instead on coal or

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[12] Biomass power, geothermal, hydropower, and other systems will tend to have larger capacities but still must be standardized and modular.
[13] RETs such as biomass power and biomass fuels have fuel costs due to growing and collecting the fuel, using plants for the solar collectors rather than a constructed collector.
[14] In the future, geothermal technologies may be developed to mine heat from hot low permeability rock. In one concept pressurized water is pumped down into fractured strata to extract heat before returning to the surface to power the geothermal plant.
[15] For example, compound semiconductors such as cadmium telluride and copper indium diselenide are photovoltaic materials.
[16] In the future, advanced gas turbines will also be used for much higher efficiencies and lower costs.
[17] Kelly et al. (1993).

nuclear plants.) However, if iRETs are to make very large contributions to electricity supplies in the longer term (50 percent or more), technologies are needed that would make it possible to store energy for many hours at attractive costs; strong candidate options include compressed air energy storage[18], high-temperature heat storage in molten salts for solar thermal-electric conversion systems,[19] and reconfiguring existing hydroelectric plants with extra turbine capacity to provide electric backup.[20]

Many RETs will be sited in distributed configurations[21] much closer to customers than is the case with conventional power-generating technologies. When such systems are integrated into electric grids, new control technologies and strategies and new power management entities (e.g., the "distributed utility") will be needed to exploit optimally the potential economic benefits offered by such systems and integrate them into the grid in ways that ensure high-quality electric service.[22] Similarly, new control technologies and management techniques will be needed for integrating RETs with fossil fuel technologies for use in applications remote from utility grids.

Changing R&D Priorities

Much progress has been made in identifying and substantially developing the most promising technology paths for economically capturing the energy of these renewable resources and terminating activities that do not appear promising.

Technologies that have been dropped—justifiably—from the R&D portfolio include Ocean Thermal Energy Conversion (OTEC), solar ponds, wave energy, and others. OTEC and solar ponds operate off very small temperature differences and so have very low thermodynamic conversion efficiencies, thus requiring the movement of huge amounts of fluid in large structures under difficult conditions. Their prospects are poor.

However, budget constraints and the pressures to show clear technical and market progress have also forced reductions in important longer-term research areas. These include fundamental research on the properties of semiconductors for photovoltaics, high-temperature materials and long-life reflectors for solar thermal systems, fatigue-resistant materials for wind turbine blades, geochemical characterization tools for geothermal reservoirs, computational aerodynamic models for wind turbines, and so forth. It will be important to increase fundamental research in these areas while maintaining applied technology R&D and encouraging the development of viable industries and markets. Some of this is being done, but more is needed. This should be done through closer ties between the DOE fundamental research programs and the applied technology programs in the DOE Office of Energy Efficiency and Renewable Energy (EERE). Mechanisms for doing this are discussed in Chapter 7.

MARKET DEVELOPMENT

Renewable energy companies seek to build markets while reducing risk. For example, many companies focus on aggregating high-value niche markets to increase production volume and force costs down. PVs got started in part by powering satellites, then remote telecommunication systems on earth, and

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[18] Cavallo (1995), Schainker et al. (1993).
[19] De Laquil et al. (1993).
[20] Johansson et al. (1993).
[21] Examples are fuel cells in or PVs on buildings. Use of distributed generation systems provides various benefits, including lower transmission and distribution (T&D) electrical losses, reduced peak loading on distribution transformers, and improved capacity utilization of the T&D system.
[22] Awerbuch (1996).

now are being applied broadly wherever it is not economical to extend the grid—often just a few miles. Coupled with R&D, this has brought prices down by more than 10 times over the past two decades and the market is now growing at 15 to 20 percent per year, and about 100 megawatts of modules are now being produced annually.

At the time of the oil price shocks of the 1970s it was believed that market development for renewables would evolve smoothly from such niche markets to major energy markets. But as a result of the sharp declines in energy prices in the 1980s and the ongoing energy industrial restructuring, the transition to major markets is proving to be difficult for renewable energy companies. At current and projected U.S. natural gas prices, natural gas-fired combined cycle systems (NGCCs) provide electricity at lower costs than most renewable systems.[23] And, except for CO_2, emissions and other environmental impacts of NGCCs are very low.

Given the competition from NGCCs, all of these technologies face great difficulty capturing sufficient market and production scale to drive costs down. Further, it is often difficult for a company to attract financing for continued R&D and demonstration and commercialization when it might not have a net return for ten years or more. Also, in contrast to pharmaceuticals and computer technologies, the product (electricity) is a very low margin commodity for which high returns are unlikely (see Chapter 7). Electricity sector deregulation and restructuring are currently increasing these difficulties for renewables even more than they are for other non NGCC technologies. Reasons for this—real or perceived—include the higher financial risk of renewables due to their higher capital cost (but low or no fuel costs), and the higher technical risks arising because the technologies are new and unfamilar to many potential users.

This difficult situation will not persist indefinitely, however. With continued R&D, energy production costs for many RETs are projected to continue their steep[24] declines. Many are expected to become competitive with coal, either directly or in distributed utility applications over the next decade or so. Some of them could also become competitive with NGCCs. Wind and geothermal, in particular, could become competitive with NGCCs in the next ten years at sites with medium- to high-grade resources.[25]

INTERNATIONAL CONTEXT

Most global growth in the demand for energy will be in developing countries in the decades ahead. Many RETS are well-suited for these markets. The small scales and modularity of most RETs make them good fits to energy systems in developing countries. PV technology is already competitive for household lighting and other domestic uses in rural areas of developing countries where some two billion people do not have access to electricity. Wind turbines are used for pumping applications in many areas, and hybrid wind energy systems are likely to find major markets at village-scale applications. Modern small-scale biomass power systems offer farmers new income-generating opportunities while providing an electricity base for rural industrialization.

The environmental attractions of RETS will have a special appeal in developing countries. Rapid industrial growth and high population densities are creating increasingly severe environmental problems in many developing regions, especially in urban centers. Moreover, there are increasing public concerns

[23] Some geothermal systems utilizing high-grade hydrothermal resources and some hydroelectric sites have lower costs.
[24] Technologies such as hydrothermal-based geothermal and hydroelectric are already low cost and relatively mature and will not see such steep cost declines.
[25] With favorable financing (such as Municipal Bonds), wind electricity in some areas with high-grade wind resources is competitive with electricity from new NGCC plants on a cost per kWh basis.

about environmental issues, as a result of this rapid growth and the ever-greater flows of information across international borders about environmental science findings and environmental awareness in other countries. At the same time infrastructures in developing countries are generally not well developed for addressing environmental concerns through regulatory approaches that force the use of pollution control equipment on energy technologies originally developed without environmental concerns in mind. Such difficulties in meeting environmental quality goals could be largely avoided by emphasizing the deployment of RETs, which have a high inherent degree of cleanliness.

While developing countries offer large market opportunities, exploiting these opportunities also poses serious logistics challenges, especially for small companies, as these areas lack much of the necessary market infrastructure of effective financing mechanisms (e.g. banks, credit windows), distribution companies, and maintenance support. Moreover, as will be discussed below in the case of wind energy, U.S. companies are often at a disadvantage in these markets, because they are undercut by aggressive European private-public export promotion to capture and lock in those markets for themselves.

FEDERAL ROLE

Federal R&D plays a critical role in the development of these RETs, accounting for between 25-75 percent of total (public plus private) R&D, depending on the technology. The Federal investment is so large relative to industry's simply because the industry is embryonic. Without federal R&D support, development would slow dramatically and a portion of the private investment would likely also be withdrawn. It is notable, however, that private R&D investment in these technologies as a percentage of revenues is much larger than the norm for the energy industry.[26] This indicates the extent to which these companies are betting their futures — as well as the capital of their investors—on developing these technologies and markets. Federal dollars for many renewable energy projects are leveraging private investment at rates ranging roughly from $0.25 to $1.75 per Federal dollar invested.[27]

R&D alone is not sufficient to launch new technologies in the market. As discussed in Chapters 2 and 7, applied R&D is critically and inseparably linked to demonstration and commercialization as well as to fundamental research. There are substantial barriers to commercialization of RETs, including low fossil fuel prices, the low profit margins from the commodity products provided by RETs, the inadequate financial resources for commercialization of many of the small high-technology companies that are developing RETs, the tendency of larger companies to invest in less risky, near-term opportunities, the barrier to consumer acceptance posed by the high capital intensity of most RETs, inadequately developed market infrastructures for some RETs, and the market's undervaluing of the environmental benefits offered by RETs. Because of such barriers and especially because RETs provide environmental and other public benefits, temporary government support for demonstration and commercialization activities is often warranted. Efficient mechanisms to encourage market growth for embryonic RET industries are also important in order to establish a rapid "virtuous cycle" of scaling up production, driving down costs, and thereby broadening the market base, making possible further increases in production volumes and still lower costs (Chapter 7).

The links among fundamental research, applied R&D, and demonstration and commercialization activities are best forged through industry/national-laboratory/university partnerships. This helps ensure

[26] Preliminary data provided by DOE indicate that private sector R&D expenditures on various renewable energy technologies are as much as 10 percent or more of sales revenues. This is comparable to R&D expenditures as a percentage of sales in other high-technology industries, but is as much as 20 times the rate for the energy industry as a whole.
[27] Preliminary data provided by DOE in response to PCAST questions, August 1997.

market relevance in the R&D undertaken, engages the country's best intellectual talents on critical scientific and engineering needs, accelerates the transfer of the R&D into the economy, and leverages Federal dollars.

BUDGET RECOMMENDATIONS AND POTENTIAL IMPACTS OF THE R&D

The Panel believes that, with a strong R&D program coupled to appropriate demonstration and commercialization incentives (see Chapter 7), many RETs in the EERE R&D portfolio have good prospects of eventually becoming fully competitive with conventional energy technologies in widescale applications, as is indicated by the discussions of individual technologies in the next section of this chapter and in more detail in Appendix F. This assessment of the outlook for RETs is shared by various groups, such as the Shell International Petroleum Company and the IPCC, as noted above.

The Panel believes that roughly doubling of the overall R&D budget (1997 to 2001) would be required to provide good prospects that RETs will be able to make large contributions to global energy during the first quarter of the next century. **The Panel's budget recommendations and the activities that would be targeted by the increased budgets are summarized in Table 6.1 and discussed on a technology-by-technology basis in the next section. For technologies that continue to show promise, budgets should be sustained at such elevated levels for several years (the number varying with the technology) until they become established in the market and industry can shoulder a greater share of needed continuing R&D;**government's role can then be reduced to supporting mainly longer-term R&D.

Consider first wind power; though the technology is not yet mature, remarkable technological progress has been made, and it is expected that most of the principal R&D goals can be met by 2005; Federal R&D budget support could thereafter begin to decline. In the case of biopower most major program goals could probably be reached in a decade's time, adapting to biomass R&D that has already been carried out for coal; it might be feasible to begin reducing Federal R&D support at about that time. For many other technologies it will take longer, but in nearly all cases principal program goals should be achievable in less than 20 to 25 years.

Calculations are presented in Table 6.2 to illustrate potential impacts of selected RETs in relation to R&D support levels estimated as needed to meet major program goals. The calculations are for the U.S. energy system with energy services frozen at 1995 levels. For a given technology estimates are given for the year when half of the ultimate potential market in this context could be captured by a particular RET, neglecting competition among RETs and the detailed dynamics of system evolution. Potential energy production levels and associated oil import and CO_2 emissions reductions at half ultimate market penetration are indicated. These highly simplified calculations are not projections, and the potential impacts are not additive. Nevertheless, these calculations can be helpful in understanding better the importance of R&D on various RETs in addressing climate change, energy insecurity, and other challenges.

Consider CO_2 emissions reduction that would arise for the wind plus storage scenario presented in Table 6.2, which involves displacing mainly coal electricity. Charging the total cost of R&D for wind plus storage against the CO_2 emissions reduction achieved over the 30-year lifetimes of the wind plants built until 2025 amounts to $0.06 per ton carbon (tC), a tiny cost penalty for reducing emissions. This calculation does not reflect the fact that once a low-CO_2-emitting technology is launched in the market, emissions reductions will continue indefinitely, nor does it take into account various other societal benefits offered by wind technology, such as reduced local air pollution. Because the wind, PV, and solar thermal electric (STE) + storage technologies in this table are all competing for essentially the same electricity market, the sum of the costs of all three programs should be charged against the CO_2 emissions reduction projected for just one of the scenarios; even when this is done, the R&D cost amounts to less than $0.50/tC. Thus, even a diversified RET R&D portfolio is cheap climate-change insurance. Of course, commercialization incentives (see Chapter 7) as well as R&D support would probably be needed to achieve the level of market penetration indicated in this scenario. However, because such incentives are not likely to increase the total cost of the innovation by more than a factor of two or three or four, the investment would still be cheap climate-change insurance.

The geothermal option presented in Table 6.2 is for hot dry-rock (HDR) technology. With this technology it would be possible to exploit a much larger fraction of the geothermal energy resource base than is possible with current hydrothermal technology and to provide geothermal power in most areas. HDR technology is at an earlier stage of development than the various iRET technologies, however, so that a longer-term R&D program is needed to make the technology commercially ready. But pursuing HDR technology as a long-term option in the RET portfolio would again be cheap climate-change insurance that would still make it possible to achieve significant reductions in GHG emissions in power generation during the first half of the next century.

Consider next the program for producing ethanol derived from cellulosic feedstocks as an alternative to gasoline (the last entry in Table 6.2). The total estimated cost for this biofuels program to reach the principal program goals is one of the higher cumulative R&D costs in the RETs portfolio. This program contributes to both CO_2 emissions reduction and to reducing oil imports. Suppose that the entire cost of the R&D program is charged against the benefit of reduced oil imports over the 25-year lifetimes of the ethanol plants that would be built by 2035; the cost would then be $0.04 per barrel of imported oil—again, cheap insurance against energy-supply insecurity, without taking any credit for CO_2 emissions reduction or other benefits.

Not all the technologies in Table 6.2 will be able to achieve the targeted penetrations, because of either competitive effects or unforeseen technological obstacles. An example of the latter is the possibility that land-use constraints might limit the potential for biomass production to a level lower than that required for the last two items in the table—some 13 exajoules (12 quads) per year, with contributions from both agricultural and forest-product industry residues and dedicated energy crops. The energy crops would be grown on some 36 million hectares. This is equivalent to the amount of cropland idled or in short- and long-term set-aside programs in 1992. But no one knows how much idled cropland there will be some forty years from now—some projections indicate more, others less than at present, depending on both crop yield and global agricultural market trends. However, comparable or even greater reductions in oil requirements could be achieved with much less biomass supplies and thus much less land requirements for energy crops if a shift to biomass fuels were accompanied by shifting from internal combustion engine vehicles (assumed for the calculation presented in Table 6.2) to fuel cell vehicles operated on ethanol. Fuel cell vehicles being developed with support from the Office of Transportation Technologies in EERE (see Chapter 3) operated on ethanol would require only one-third to one-half half as much fuel as internal combustion engine vehicles, with much lower local air-pollutant emissions. A sufficiently diversified energy R&D portfolio that embraces such energy-efficient end-use technologies would make it possible for RETs to play major roles in addressing the major challenges, even in the face of unforeseen technological obstacles.

Table 6.1: Proposed R&D Budgets and Activities (in Millions of As-Spent Dollars).[a, b]

Technology	R&D activities beyond current baseline, and impacts	FY97 $M	FY98 Reqst	FY99 $M	FY00 $M	FY01 $M	FY02 $M	FY03 $M
Biomass Fuels	Double number of energy crop species under development; develop crop harvest, handling, storage systems. Stimulate fundamental research on perennial species with co-support from ER at up to $2M. Develop integrated power/ethanol plant with goals of: cost of ethanol at $0.50/gallon and power at $0.04/kWh; and producing 28 billion gallons ethanol/year and 36 GW of capacity by 2020. ER to co-support key fundamental research relating to ethanol production at up to $5M level. Launch modest program to produce biofuels from synthesis gas.	28	38	58	76	94	97	99
Biomass Power	Develop biomass—materials handling; IGCC; biogasification-fuel cell; small-scale gasification-stirling engine or other systems; cofiring with coal; and other systems with associated cost-shared precommercial demonstrations. Goal of 6 GW in pulp and paper industry by 2010; 25 GW cofiring by 2030. Integrated power/ethanol plant as above. Cofiring to be cost shared with DOE fossil energy program.	28	38	63	86	89	91	93
Geo-thermal	Reactivate R&D on advanced resources, especially HDR; expand advanced drilling R&D through NADET; increase R&D on reservoir testing and modeling, increase productivity, lower costs. ER to co-support fundamental reservoir engineering science—including geophysics diagnostics and modeling, formation charaterization and fracturing for HDR,etc.at up to ~$5M.	30	30	42	49	50	51	52
Hydrogen	Program should move away from near term demonstrations in internal combustion engines. Launch initiative with DOE Fossil Energy program on innovative hydrogen production from fossil fuels combined with sequestration and with the Biofuels program on hydrogen production from biomass—additional budget for hydrogen research ramping up to $15M/year, consisting of comparable contributions from the biofuels program, the fossil energy program, and ER. ER would co-support research on advanced hydrogen storage technologies (e.g., carbon nanostructure materials) and other fundamental science issues at up to about $5 M.	15	15	16	16	17	17	17
Hydro-power	Accelerate R&D to develop fish-friendly turbines and low-head run-of-river turbines; analyze ecological/environmental impacts of hydro on a quantitative basis; examine coupling of hydro to intermittents; examine innovative financial instruments for funding activities through PMAs.	1	1	4	8	11	11	12
Photo-voltaics	Accelerate fundamental PV science—understand properties of PV semiconductors, broaden range of materials investigated, and discover new PV materials, with co-support from ER at up to $5 M. Substantially strengthen laboratory scaleup to first-time manufacturing, including reaction kinetics and reactor design, large area uniform deposition and quality control under volume production. Support engineering science for large volume, low cost production, including increased deposition rates, improved materials utilization, improved characterization techniques—especially in situ, and materials recycling. Support for system integration and BOS work—particularly to improve inverter technology cost, performance, and reliability.	60	77	105	130	133	137	140
Solar Thermal	Strengthen power tower and dish-stirling technology development, including molten salt storage and optical materials research, and solar manufacturing technology initiative. Launch new initiatives in advanced high temperature receivers, brayton cycles, and fuels production. Co-support from ER at up to about $5 M for study of radiation-matter interactions at high solar fluxes and high temperatures, materials science relating to high-temperature STE technologies, and materials science relating to the development of low-cost reflectors.	22	20	32	43	44	46	47

Wind	Strengthen R&D in advanced 3-D computational fluid dynamics, fundamental R&D on advanced materials for blades, lightweight adaptive structures to passively reduce loads and extend fatigue life, direct-drive variable speed generators, hybrid systems, system integration—especially with large-scale storage systems or hybrids, advanced controls, etc.; and conduct field tests, particularly in collaboration with developing countries. Launch strong wind manufacturing technology initiative. ER to co-support materials, computational, and other research at up to about $5M. Conduct research in environmental issues, particularly avian.	29	43	53	65	66	68	70
Systems and Storage	Extend storage R&D, particularly for system integration with intermittent renewables; conduct highly leveraged test of CAES with wind. Develop R&D program on T&D	32[c]	46	51	54[d]	55	57	58
Solar Buildings	Expand R&D: in efficient/passive whole building design; building-integrated PVs and thermal systems; low cost solar water heaters and other thermal collectors. Develop building energy and materials design tools. Support international buildings R&D and design tool development. ER to co-support basic materials studies at up to about $2.5M—temperature/UV resistant polymers for low cost thermal collectors; phase change storage materials; electrochromics	3	4	6	9	9	9	9
Interna-tional	R&D in applications-specific systems integration and development; international collaborative R&D; technical and policy analysis; technical assistance; training	1	7	11	13	13	14	14
Resource Assessment	Integrated resource assessment across biomass, hydro, geothermal, solar, wind, and CAES; further develop geographic information systems; develop advanced resource mapping tools and techniques, Systematically extend resource assessment studies to developing countries.	(1)	--	5	5	6	6	6
Analysis	Strengthen program focus on and conduct systematic analyses of technologies—distributed utility systems, minigrid systems, systems integration and intermittent integration with utility systems; and of strategic analysis of technology opportunities within regulatory restructuring. Extend analysis of markets—financial analyses, options valuation; and of policy mechanisms—net metering, green pricing, portfolio standards, economic impacts; externalities, etc.	(3)	--	4	5	6	6	6
Other	Renewable Energy Production Incentive; Solar Tech Transfer; Renewable Indian Energy Resources; Program Direction; and others. These activities were not examined by the Task Force and are included here as a constant baseline only for consistency with budget documents.	21	26	25	26	27	26	29
TOTAL		270	345	475	585	620	636	652

[a] Activities are to be carried out through industry/national lab/university partnerships with cost sharing by industry. The focus is on R&D activities, with some precommercialization demonstrations. Commercialization activities are considered separately in Chapter 7. All activities indicated here as "co-supported" by ER are for fundamental research activities that are to be both cofunded and comanaged by the particular energy technology program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7; support from ER would come from new funds or funds made generally available as programs normally turn over.

[b] Note that many of these budgets will ramp down in the 2005-2010 time frame as the largest portion of the potential cost reductions is achieved and the embryonic renewable energy industry strengthens. In all cases, budgets are to be re-examined periodically for performance and adjusted accordingly.

[c] This is the FY97 level and does not include the increase from FY97 of $19.75M to $36M for superconductivity already agreed to by both House and Senate in the FY98 budget.

[d] Superconductivity R&D remains at $32M; EMF R&D from $8M to $0; Storage R&D from $4 to $12M; T&D from $0 to $10M.

Table 6.2: Potential Impacts of SelectedRETs in Relation to R&D Activities

RET	Principal Program Goals are Reached In	Cumulative Program R&D Budget until Principal Program Goals Are Reached (Millions of 1997 dollars)	When Half of Ultimate Potential at 1995 Market Levels Is Realizable	Annual Energy Production Rate by RET at 50% of 1995 Market Capture	Oil Import Reduction at 50% of 1995 Market Capture (Million Barrels per day)	CO_2 Emissions Reduction at 50% of 1995 Market Capture (Million metric tons Carbon per Year, MtC/y)
Intermittent Wind[a]	2005	$ 450	2025	230 TWh	-	40
Wind + Storage[a]	2005	$ 480 [b]	2025	1070 TWh	-	250
Intermittent PV[a]	2015	$2100	2035	230 TWh	-	40
PV + Storage[a]	2015	$2130 [b]	2035	1070 TWh	-	250
Intermittent STE[a]	2015	$ 690	2035	50 TWh	-	7
STE + Storage[a]	2015	$ 690	2035	880 TWh	-	230
Geothermal (HDR)[c]	2020	$ 660	2050	1540 TWh	-	360
Biopower[d]	2007	$ 740	2035	830 TWh	-	220
Biofuels[e]	2015	$1440	2035	69 x 10^9 gallons EtHOH	3.6	150

[a] Without storage half the potential for wind or PV involves displacing 7.5% of average electricity generated; for STE the potential is 1/5 as large, because current electricity generation on land areas suitable for STE technology accounts for 1/5 of total U.S. generation. With storage 50% of coal electricity also displaced by wind or PV or STE systems; with storage, baseload wind or STE systems can export power to other regions.

[b] Includes for energy storage R&D $4 million/year (1999 to 2005) in wind case and $2 million/year (1999 to 2015) in PV case.

[c] Half the potential involves displacing half of all electric generation. The estimated emissions reduction is for 207 GW of baseload geothermal displacing baseload fossil fuel power (90% of coal-based generation and 10% of oil and gas-based generation).

[d] It is assumed that half the potential is 88 GW of molten carbonate fuel cell byproduct power in producing 69 x 10^9 gallon/year of ethanol plus 15 GW of integrated gasification combined cycle replacement capacity at pulp and paper mills, displacing coal power in both instances.

[e] Assuming neat ethanol use in internal combustion engine-powered light-duty vehicles that account for half of light-duty-vehicle miles traveled.

RENEWABLE ENERGY TECHNOLOGIES, R&D NEEDS, AND OPPORTUNITIES

Described below are RETs; their R&D needs and budget requirements; and new initiatives that could significantly address U.S. economic, environmental, and national security challenges. This discussion is highly abbreviated; Appendix F provides a more detailed basis for understanding and evaluating these technologies, along with cited source materials.

Wind

Wind is an intermittent renewable resource for which estimated recoverable moderate- plus better-quality wind resources in the United States are more than three times the total U.S. electricity generation rate.[28] Although 95 percent of the potential is in the Great Plains, there are also substantial resources along coasts and mountains. Estimates of the global wind-electric potential that is practical to exploit range from about two[29] to five[30] times the current global electricity generation rate.

Environmental Issues

Wind plants produce no air pollutants or GHGs. However, concerns have been raised about bird kills. Bird kills are not likely to be a problem in most areas; where they are a problem, this will probably be dealt with largely by restrictions on wind-farm siting in bird migration pathways or in dense avian population centers, although technical fixes (e.g., use of tubular towers to reduce perching) can also reduce the bird-kill potential. Other concerns are noise and aesthetic impacts. Engineering innovations have reduced noise levels to the extent that noise is a problem only if turbines are sited within a few hundred yards of a residence. Aesthetic concerns will tend to be offset—in many areas—by the royalty payments from wind power producers, which in the Great Plains could be comparable to land rents for croplands.

Progress and Prospects

Wind power costs have fallen rapidly; new grid-connected wind systems without storage are being installed in areas with good wind resources at costs of 5-6 cents/kWh with corporate financing and even below 4 cents/kWh with favorable financing (e.g. via municipal bonds).[31] Globally, wind power capacity is being installed at a rate of 1,300 megawatts per year, worth roughly $1.3 billion per year. Wind systems are reliable and readily maintainable, and there is a clear technical path for substantially bettering cost and performance.

The cost of wind-generated electricity can be substantially reduced in the near to midterm through further R&D and demonstration and commercalization activities. Analyses carried out for DOE through the National Renewable Energy Laboratory (NREL) indicate that by 2005 costs with corporate financing could reach 3.4 cents/kWh in areas with moderate-quality (class 4) winds and 2.8 cents/kWh with high-quality (class 6) winds.[32] These costs are lower than for coal-fired generation and comparable to NGCC power costs on a kWh basis. Of course, economics depend on value as well as cost. Wind power is always at least as valuable as the fuel consumption its deployment obviates, but it also has capacity value. At low penetration levels, wind power plants typically have the same capacity value as fossil-fuel power

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[28] Cohen (1997).
[29] WEC (1994).
[30] Grubb et al. (1993).
[31] Cohen (1997).
[32] Cohen (1997).

plants with the same annual output, but the capacity value declines with system penetration to about half the initial value by the time wind accounts for 5 to 10 percent of the electric energy provided by the power system.[33] The value of wind power at high penetrations can be increased if wind power is integrated with energy storage. Compressed air energy storage (CAES) and possibly other storage technologies could make it possible to provide even "baseload" wind power, without substantially increasing the electricity cost.[34] Because baseload power can be transmitted long distances at relatively low cost it becomes feasible to consider exporting wind power from the Great Plains to distant markets when wind electricity prices become sufficiently low (see Box 6.1).

Markets

Although U.S. entrepreneurs pioneered modern wind turbine designs, they have found it difficult to participate in the global boom. Wind markets in the United States have largely disappeared—totaling less than 1 percent of the global market in 1996—because of policy changes, low cost natural gas, and the onrushing deregulation of the electricity sector. Wind markets in Europe have proven difficult to penetrate for entrepreneurial U.S. firms, with their limited resources and the presence of numerous European wind companies with European government R&D support at a level of some $150 million per year (compared to about $30 million in the United States). U.S. companies' efforts to participate in developing-country markets have been undercut by aggressive public-private export promotion by Europeans aiming to capture and lock in those markets for themselves. For example, 9 of 13 wind farms in China received grants or concessionary government loans from European countries, typically covering half of installed costs at 0 percent interest for 10 or more years. In mid-1997, a U.S. company—FloWind—filed for Chapter 11 protection, in part because it was locked out of the Indian wind market by market standards and certification procedures; in turn, these standards were the results of a strong foreign export promotion program that included concessionary financing for foreign wind company equipment.

The DOE Program

The program consists of (1) applied research (long-term activities aimed at expanding the technology base by addressing fundamental engineering and technical issues and at better understanding environmental issues—such as through avian research); (2) turbine research (developmental activities aimed at helping U.S. industry incorporate advanced technology into new wind turbines via cost-shared industrial partnerships): and (3) cooperative research and testing (technical support for industry, including support to help industry obtain internationally-recognized turbine certification). The resource allocation among these areas for FY 1996 was 34 percent, 47 percent, and 19 percent, respectively. About two-thirds of the budget in the Program is committed to near-term R&D.

Evaluation and Recommendations

Despite dramatic advances, wind technology is immature and requires further R&D. **Priority should be given to advanced technologies: improved airfoils, including advanced 3-D computational modeling to determine flows and the transition to turbulent flow and separation; lightweight adaptive structures that will passively reduce loads and extend fatigue life; direct drive, variable speed generators, electromechanically controlled pitch and flexible hubs; system integration, including advanced controls and storage systems; advanced wind hybrid systems, including system architectures, controls, advanced storage systems, and field testing—particularly in developing**

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[33] Grubb et al. (1993).

[34] Cavallo (1995).

regions; manufacturing technology, including for direct drive generators and turbine blades; and fundamental research such as advanced materials for blades. Attention should also be given to wind forecasting and resource assessment, environmental impacts (including ongoing avian research), and the development of strategies for exploiting large wind resources (e.g., in the Great Plains) that are remote from major electricity markets.

The current wind energy budget is not adequate to support these activities. **The EERE budget for wind should be increased from $29 to $70 million per year (see Table 6.1). The increment should be made up of comparable contributions: (1) for core research (particularly for direct drive variable speed systems and lightweight structures), and (2) to support manufacturing technology, hybrid systems development, and systems integration and storage research. In addition, up to about $5 million per year from the increment plus matching funds from Energy Research (ER) should be provided for fundamental research problems, including computational modeling of three-dimensional aerodynamic effects near turbulence and separation, and research in basic materials for very long blade lifetimes. This fundamental research should be both cofunded and comanaged by the wind energy program and ER in the manner and under the conditions described in the R&D management section of Chapter 7.**

With development of low-cost wind turbines by about 2005 and the launch of a large-scale wind industry through efficient policy mechanisms (Chapter 7), funding for wind technology development could then be gradually reduced as industry resources grow; the remaining Federal program would then be focused on longer term advanced research, which would be much less costly.

Box 6.1: A Vision for Wind Energy

DOE projects that wind power costs will decline to 2.8-3.4 cents/kWh and 2.3-2.8 cents/kWh by 2005 and 2030, respectively, assuming corporate financing.[a] If multi-gigawatt wind farms were integrated with CAES systems, baseload electricity (with a 90 percent system capacity factor) could be produced from this wind energy for 3.7-4.3 cents/kWh and 3.2-3.7 cents/kWh by 2005 and 2030, respectively. These costs are sufficiently low that baseload wind power would often be competitive if exported from the Great Plains to distant markets. For even the most remote markets (with ~ 1200 miles of transmission) the cost of delivered electricity would be only 5.0-5.4 cents/kWh in 2030 (see Appendix F). Thus most markets in the United States could plausibly be served with baseload wind power from the Great Plains at costs of this order or less.

A possible target market would be the replacement of old fossil-fired baseload plants when they are due to be retired. Such power plants account for about 30 percent of U.S. CO_2 emissions. Almost all will be 30 or more years old by 2020 and could, in principle at least, be replaced by wind power upon retirement. Such replacement would require an average annual growth rate for wind systems from 1998 to 2020 of about 33 percent. This is a very rapid growth rate, but is less than the growth rate of the U.S. nuclear industry from 1957 to 1977. Because wind turbines are modular, will be mass produced in factories, and require much less material per unit capacity, high growth rates would be easier to achieve.

Such a strategy of using baseload wind power as an alternative to fossil power could also be pursued in China, which, like the United States, has huge wind resources in areas (e.g., Inner Mongolia) that are remote from population centers.

Pursued in the United States or China, this is an aggressive vision, but one which suggests the magnitude of the potential. How such an approach would fit in a restructured electricity sector must also be examined.

[a] Cohen (1997).

Although leadership in wind turbine technology is passing to Europe, the United States has the opportunity to regain a leadership role through a combination of: (1) an aggressive R&D program (as outlined above) aimed at bringing down costs to levels at which wind can compete in a restructured electric industry, and (2) appropriate commercialization incentives (see Chapter 7) designed to accelerate industrial development while maximizing the use of market forces in bringing about cost convergence with fossil fuel energy. The U.S. emphasis on lightweight, low-cost designs can be an important competitive advantage compared to the heavy and expensive European systems. In the near- to mid-term, while these technology development efforts are under way, the challenge in developing-country markets posed by foreign concessionary finance should be addressed by more proactive responses by U.S. export agencies such as the Export-Import Bank. Conducting carefully targeted field tests and providing technical assistance to the multilateral banks can also help open new makets (see Chapter 7).

Photovoltaics

PV technologies convert sunlight directly into electricity using solid-state devices. Most technologies use flat-plate collectors that convert diffuse as well as direct sunlight into electricity. At a typical 10 percent efficiency, 600 square feet of collectors are needed to generate electricity at the average U.S. household use rate at a site with averageinsolation.

Environmental Issues

Electricity is produced with zero pollutant and GHG emissions. Emissions associated with the manufacture of PV systems are small for the most promising PV technologies, largely because the energy required for manufacture is a small fraction of the energy produced over the system lifetime.

Progress and Prospects

Global PV production in 1996 was 89 megawatts; U.S.-based production accounted for 44 percent, and about two-thirds of U.S. production was exported. Although current PV electricity prices are much too high for grid-connected PV systems to be competitive, PV is typically the least costly electric technology for small-scale remote applications ranging from callboxes along U.S. freeways to lighting for rural households in developing countries. Market strategy consists of: (1) identifying niches where the technology is cost-effective today against conventional energy; (2) aggregating these demands to scale up production; and (3) driving down prices by technology improvements, increases in the scales of production, and learning-by-doing cost reductions that arise as cumulative production increases. These cost reductions expand the range of market niches where the technology is cost-competitive. This market strategy will allow PVs to penetrate ever larger markets, in the following progression: rural remote, village minigrid, distributed grid-connected, peaking, and finally intermediate and baseload power applications.

Because of the absence of scale economies for deployed systems, because PV systems can be operated unattended, and because they produce no emissions, decentralized PV production near users will probably dominate the PV future. Of particular interest are building-integrated applications in which the active PV material is layered on materials that form the building's skin, such as shingles or other roofing elements, skylights, or siding. As costs can be shared with structural components of buildings, such systems can be less costly than PV in centralized power plants. In addition, the electricity produced will typically be more valuable than central-station electricity, because of reduced transmission and distribution losses, reduced need for transmission and distribution investment (even for grid-integrated PV systems), and increased electrical system reliability and other benefits, so that PV can often be competitive even with electricity produced at lower cost from central station power sources.

Sharp cost reductions have been achieved. Installed PV system costs have fallen from $17,000 per peak kilowatt in 1984, to $9,000 per kilowatt in 1992, to $6,000 in 1996. The lowest costs achieved to date have been for grid-connected rooftop systems. A leading manufacturer of amorphous silicon (a-Si) technology projects that costs for installed rooftop PV systems based on the use of its a-Si modules will be $3,000 per kW by 2002.[35] At this installed cost, the Utility Photovoltaic Group has estimated that the U.S. market for grid-connected, distributed PV systems (including residential and commercial building applications and transmission and distribution grid support) would be 3,300 to 4,300 megawatts, and the theoretical potential (from the residential customers' perspective) for residential rooftop applications would be about 40,000 megawatts (see Box 6.2).[36]

With strong R&D and efficient commercialization support (see Chapter 7), it should be feasible to reduce PV system costs to $1,500 per kilowatt or less by 2010 and to $1,000 per kilowatt by 2020. The 2020 goal would make possible PV electricity costs in the U.S. of about 7 cents per kWh with corporate financing or less than 5 cents per kWh with home mortgage financing (as would be appropriate for many residential rooftop applications) in areas of averageinsolation (1800 kWh/m^2/year).

The DOE PV Program

DOE program support covers activities ranging from applied research to demonstration. Of the $60 million FY 1997 budget, 49 percent was for strategic R&D (for the Thin-Film Partnerships, university partnerships, materials and cells research), 19 percent was for technology development (PVMat), and 32 percent was for systems engineering and applications (PV:Compact, PV:Bonus, Systems Development, International Programs). DOE support was complemented by about $100 million in private R&D investment; industrial representatives who met with the Renewable Energy Task Force described the DOE program as fundamental to their efforts and indispensable to PV development.

PV progress has been strong on many fronts, especially for thin-film technologies, all of which offer the potential for very low module costs. Among thin-film options, amorphous silicon (a-Si) is already commercial technology; competing vendors have just built 5 and 10 megawatt per year module production facilities. Efficiencies for laboratory cells of cadmium telluride and copper indium diselenide, polycrystalline thin-films that are potential competitors to a-Si, have increased from 6 to 8 percent in 1976 to 15 to 17 percent at present. At the developmental level, there has been a doubling of system lifetimes since 1991, and sharp cost reductions. Under PVMat (a PV Manufacturing Technology initiative launched in 1990, for which 43 percent of the $118 million cost has been provided by the industry partners) module manufacturing costs fell from an average of $4,500 to $2,000 per kilowatt between 1992 and 1996, and, as a result of PVMat technological improvements, average and least costs are projected to reach about $1,200 and $1,000 per kilowatt, respectively, by the time cumulative production capacity reaches 300 to 350 megawatts per year.

Assessment

A substantially expanded PV R&D and commercialization program is called for in light of the multiple societal benefits offered by PV technology, the dramatic progress that has been made, the good prospects for much further gains, and the need for a strong government role in launching a PV industry. Program expansion is needed in all areas, but six areas relating to both R&D and demonstration and

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[35] Forest et al. (1997).
[36] Marnay et al. (1997).

commercialization are singled out here for special attention: (1) balance of system technology development, (2) PVMat, (3) fundamental research, (4) PV commercialization, (5) assessments of distributed benefits, and (6) developing country markets.

Box 6.2: A Vision for Photovoltaic Electricity

In the Spring of 1997 the President announced a Million Roofs Initiative to accelerate the commercialization of photovoltaic (PV) technologies. The goal is to install some 3.0 gigawatts of PV systems on rooftops of 1 million buildings in 325 cities by 2010. The Federal government will provide funds directly to communities and builders to organize programs to promote the use of PV systems. Various incentive schemes will be used. One will be "net metering," which involves running an electricity meter backwards when rooftop PV systems are exporting electricity to the grid, giving consumers credit for exported electricity at the utility's electricity selling price.

What size of market could be supported by net metering? A recent Lawrence Berkeley Laboratory study[a] addressed this question in a very preliminary but suggestive way for 4 kW systems deployed on roofs of single-family dwellings as a function of the PV system price, assuming the systems are paid for with 30-year loans at a 6.5-percent inflation-corrected mortgage interest rate and that customers would be willing to pay a "voluntary premium" of $4 per month more for electricity with PV systems on their roofs. Thus a system was judged to be "cost-effective" if the levelized cost of the PV-generated electricity was less than $4 per month more than the cost of the same amount of electricity purchased from the utility. The size of the U.S. market was found to be zero at the current rooftop PV system price of $6,000 per kW, but the theoretical potential (actual rooftop orientations and consumer preferences were neglected) was estimated to be 40,000 megawatts (10 million rooftops) with an output equivalent to 3 percent of U.S. power output at $3,000 per kW, a price level that might be realizable as soon as 2002. If, beginning in 2002, PV systems were installed for this market at a rate of 100 megawatts per year, 40,000 megawatts of cumulative production could be reached by 2015 if production were to grow 39 percent per year. Such a growth rate is very high, but not implausible; between 1957 and 1977, U.S. nuclear capacity grew at an average rate of 36 percent per year. Both an aggressive R&D program aimed at making cost-cutting technological improvements and commercialization incentives (see Chapter 7) would be needed to realize such a scenario.

[a] Marnay et al. (1997).

Historically, the focus of PV technology development has been on PV modules. In light of overall budget constraints, this focus has been appropriate, because modules have dominated costs. However, as noted, module costs have been falling dramatically, so that balance of system (BOS) costs are accounting for a larger share of installed costs. A more balanced effort giving greater attention to BOS issues is needed. Also, the successful PVMat program should be extended (beyond the scheduled near-term sunset provision), because many manufacturing issues remain to be resolved, especially for the advanced thin-film technologies. The weakest part of the DOE PV program is fundamental materials science research. This weakness is reflected in both the lack of fundamental understanding of the scientific issues relating to thin-film PV technologies and the narrowness of the choices of base materials for modules. Each of the major thin-film technologies being developed with DOE support has great promise, but there is also uncertainty over the long-term prospects of each, and there are other new opportunities that could be evaluated from the perspective of fundamental science. The long-term outlook for PV would be enhanced if there were a broader materials basis for the technology.

There have been some important links between the NREL applied research and technology programs and Basic Energy Sciences (BES) fundamental research programs, but overall these links have been weak. In 1996 a new program was created, which has the promise to deal effectively with the fundamental science challenges facing PV: named the High Efficiency Photovoltaics Program (HEPP), it is sponsored by the Division of Materials Science of BES through its Center of Excellence for Synthesis and Procesing of Advanced Materials. Strong NREL participation in the HEPP is expected to facilitate cooperation between BES and EERE. Substantial new funds should be provided to the DOE for HEPP.

As noted, PV electricity in distributed configurations is worth more than in centralized power plants, even when the PV system is grid connected. Yet the economic value to the utility of PV-generated electricity varies markedly not only from one utility to another but also from one feeder to another within a single utility's service territory. DOE should provide analytical support to appropriate state agencies and utilities to help them assess the distributed benefits of PV technology throughout their utility systems, thus promoting a better understanding of the most cost-competitive market opportunities.

The Administration has announced a Million Roofs Initiative to stimulate PV systems integration and commercialization of PV technology for applications on buildings (see Box 6.2). This initiative could be very effective in launching a PV industry and bringing down PV prices, if supporting commercialization policies are adopted (Chapter 7).

International opportunities are enormous. Most of the growth in global electricity demand will be in developing countries. Some 2 billion people do not have access to electricity and small PV systems are often the most cost-effective means of getting it to them at present; there are similarly large markets in poorly served areas for communications, water supply, and a host of productive activities. During the period from 2000 to 2005, PV prices should be low enough for PV to be deployed in the much larger grid-connected, distributed generation markets as well. Increased support for applications development, codes and standards, training, collaborative RD&D, and other activities in support of international market development for U.S.-based production is needed.

Budget Recommendation

In light of the potential benefits, the multiple challenges and opportunities, as well as the large increases that are being made in PV R&D and commercialization expenditures that are being made in Japan and Europe, **it is recommended that the PV R&D budget be increased from $60 to $140 million per year (see Table 6.1). The added funding should be used to support laboratory scaleup to first-time manufacturing, engineering science to develop large-volume, low-cost production, and R&D on system integration and inverters and other BOS components. In addition there should be a major expansion of fundamental materials science research through the newly-formed HEPP, funded at a level up to about $5 million per year from the PV program, with matching funds from ER. This fundamental research should be both cofunded and comanaged by the PV program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.**

High-Temperature Solar Thermal

High-temperature solar thermal technologies use mirrors to concentrate the sun's rays onto receivers, in which the solar heat is recovered. The DOE Program is aimed at developing solar thermal electric (STE) systems that make electricity from the recovered solar heat in conventional thermal power cycles.

Technology Attributes

STE systems have the long-term potential to provide a significant fraction of the world's electricity needs; however, because these systems can use only direct rays from the sun, they must be located where there is good direct normal insolation with minimal cloud-induced scattering, e.g., the southwestern United States, the Middle East, and desert areas of many developing countries.

STE applications range from central-station to modular, remote power. STE systems can be hybridized to run on both solar energy and fossil fuel; they can also be designed with integral thermal energy storage that can make solar-only STE systemsdispatchable.[37]

Hybrid systems in which solar heat is used to provide modest (10 to 20 percent) contributions to steam generation in fossil power plants (NGCCs or coal plants) make it possible to (1) gain valuable commercial experience with STE technology and build up STE industrial capacity in the context of familiar conventional generating technology, (2) exploit economies of scale for the power conversion technology without risking large solar investments, and (3) increase the value of the generating capacity to the utility and thereby increase the electricity rate the utility is willing to pay for electricity generated.

Environmental Issues

Air pollutant and GHG emissions are associated only with the fossil fuel fractions of hybrid STE systems. STE plants would be no more land-use intensive than some coal plants. Water supply availability could constrain development in water-scarce regions if wet cooling towers are used, but this problem could be addressed various ways (e.g., by using completely dry conversion technologies such as regenerative gas turbines).

Present Situation

The only STE technology with commercial experience uses parabolic trough collectors coupled to steam turbine power units and natural gas backup; some 354 megawatts was installed in California, 1984 to 1991; as a result of this experience capital costs for the solar portion fell from $4500 to $2900/kW. The company involved had to file for bankruptcy in 1991, largely as a result of the on-again, off-again extension of tax and regulatory incentives.[38] Today vendors are pursuing new projects in several countries. These plants will be able to produce solar electricity at life-cycle costs in the range 13 to 14 cents per kWh for the solar portion of the produced electricity (assuming corporate financing)—low enough to compete in some load-following and peaking-power markets.

The DOE Program

The STE program is developing advanced technologies cooperatively with industry, which has shown strong interest by its involvement in cost-shared projects averaging a 45 percent industrial contribution. Goals for 2020 are 5 cents per kWh solar electricity and 20 GW_e of installed capacity worldwide. Both the "Power Tower" (PT) that uses a field of heliostat mirrors to concentrate sunlight onto a centralized receiver and the parabolic dish (PD) that focuses sun rays onto receivers mounted at dish foci are being developed.

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[37] De Laquil et al. (1993).
[38] OTA (1995).

PT technology is being developed at scales of 100-200 megawatts for central stations; PD technology at scales of 5-100 kilowatts for distributed markets, especially developing country markets. PT R&D involves developing low-cost heliostats and associated drives, high-temperature receivers, and high-temperature molten nitrate salt thermal storage, and understanding system integration issues. Thermal storage makes it possible to decouple solar energy collection from its conversion to electricity and to provide dispatchable power. If heliostat cost goals are met, PT technology with approximately 13 hours of storage could provide, by 2020, 5 cent per kWh baseload solar-only electricity.

At present estimated electricity costs are higher for PD than for PT technology; but future costs might be comparable, if hoped-for economies of mass production are realized. PD R&D is focused on developing low-cost, reliable concentrators and on using energy-efficient Stirling engine electric generators; however, realizing low maintenance costs and long system lifetimes are major R&D challenges for these engines.

Assessment and Recommendations

The program is well structured to meet the challenges of developing the targeted technologies and well-coordinated with industry. Emphasis on molten salt storage, a key enabling technology, is appropriate. The refurbishing of the 10 megawatt Solar One pilot plant (in Barstow, California), which successfully proved the PT concept as a workable STE technology, into Solar Two as a test-bed for molten salt-based PT technology is key to understanding systems integration issues before building commercial-scale demonstration plants. **Development of low-cost thin-film reflectors for use in both heliostats and dish receivers warrants high priority. SolMat, a new initiative to help develop manufacturing techniques, could prove to be as important as PVMat has been for PV technology.**

The program's major shortcoming is inadequate attention to the possibilities for achieving higher efficiencies and lower costs by operating receivers at higher temperatures that could accommodate gas turbine cycles. **Pursuing higher temperature technology would require adding to the Program new heat transfer fluids, receiver concepts, and storage concepts; strong ties with ER in radiation-matter interactions, materials research, and thermal storage at high temperatures are needed. The program should work closely with DOE Fossil Energy (FE) to develop appropriate gas turbine cycles. It should also pursue collaborative R&D efforts with foreign STE R&D groups, several of which have strong efforts underway on advanced high-temperature receivers; these collaborations could include advanced systems studies, component development, and the construction of pilot plants designed to explore systems issues. Finally, the Program should be broadened to include fuels production by using high-temperature solar heat to drive endothermic reactions. In particular, the STE and H_2 programs in EERE and FE should collaborate on high-temperature receiver development suitable for making H_2 from fossil fuels and the associated high-temperature chemistry research.**

These activities require expanding the budget from $22 million to $47 million per year (see Table 6.1). The increment should include funding at a level of up to about $5 million per year, with matching funding from ER, for fundamental research on science issues related to high-temperature receivers and materials science issues relating to the development of low-cost reflectors for both heliostats and dish receivers. This fundamental research should be both cofunded and comanaged by the STE program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

Geothermal Energy

Geothermal energy is the heat energy inside the earth. It is used today in the western United States to produce electricity or heat from underground steam or hot water (hydrothermal) resources. This is the only type of geothermal resource that is currently commercially developed. Hydrothermal resources are limited, however; in the future, Hot Dry Rock (HDR) and other advanced resources might be tapped. Another component of geothermal technology that is also being developed is the ground source heat pump; currently more than 250,000 U.S. houses have them.[39]

Of geothermal resources, HDR is the largest, with more than 14 million quads of energy in hot, low-permeability, low-porosity crustal rock at depths varying from 3 to 10 km and temperatures greater than 150 degrees centigrade (C). High-grade systems, characterized by high geothermal gradients (greater than 50 to 60 C/km), are located primarily in the West and Midwest of the United States, whereas lower-grade systems with gradients of 25 to 40 C/km are widely distributed. HDR requires fracturing of the underground rock formation to allow water to flow through and heat up before returning to the surface to power a generator. Extensive research is needed to understand these underground rock formations, how to fracture them reliably and cost effectively, and how to move water through them with limited water losses or mineral uptake.

The main attributes of geothermal energy include the following:

- Low-cost, reliable, baseload electricity is provided by hydrothermal systems.
- There is low land use in comparison to fossil, nuclear, and other renewable energy resources.
- There are negligible carbon emissions and minimal solid waste for most geothermal resources.
- H_2S, NH_3, and particulate emissions are controllable for hydrothermal systems.
- HDR systems are closed loop and emissions-free.
- Site specific corrosion and solids deposition effects may require special equipment and materials.
- Seismic risks appear low and manageable with proper system design and operation.

Progress and Prospects

Currently the United States is the largest producer of geothermal electric power, with an installed capacity of 2733 MW. Worldwide capacity is now greater than 7000 MW with much growth occurring in developing countries; projections indicate there will be more than 10,000 MW total installed by 2000. In the United States, with favorable energy markets and financing, an additional 5000 MW could be added by 2010. Although hydrothermal-based geothermal energy can make an important contribution to energy needs, wide-scale use is not possible because of the limited size of the resource and because it is confined to areas associated with recent volcanism or near the boundaries of tectonic plates, such as along the Pacific

[39] Mock, et al. (1998), Wright, et al. (1997)..

coast. If HDR resources can be developed, then geothermal energy can become widely available for supplying electricity and heat.[40]

The U.S. geothermal industry has worldwide technical leadership in developing geothermal resources and installing power plants. There is, however, significant competition from the Europeans and Japanese who are investing more than $80 million per year in R&D and are interested in both advanced hydrothermal and HDR technology. Collaborative work between the United States, Europe, and Japan is not being carried out, with the exception of a few informal information exchanges and conferences, and a small IEA-supported program.

The DOE Geothermal Program, Assessment, and Recommendations

DOE (and before that, ERDA) has had an active geothermal energy RD&D program for more than 20 years. Considerable progress has been made in increasing the range of geofluid operating conditions (temperature, pressure, and chemical and phase composition) and conversion efficiencies of hydrothermal power plants; improving drilling technology and downhole diagnostic methods; and advancing reservoir modeling to predict long-term, thermal-hydraulic performance. Funding cutbacks in the early 1980s severely reduced R&D for long-term options (HDR, geopressured, and magma) to a point where all field and laboratory work has been discontinued. This is an important area with a high long-term potential.

RD&D recommendations for the DOE Geothermal Program include the following:

- **Continue work on hydrothermal systems, including cost-shared work with the relatively small and somewhat fragile U.S. geothermal industry.**

- **Reactivate RD&D for advanced concepts with the top priority given to high-grade HDR systems.**

- **Increase participation of other DOE programs and other government agencies in the National Advanced Drilling and Excavation Technologies program; this program will assist in the leveraged development of advanced drilling technology to lower costs--opening up a larger fraction of the massive U.S. geothermal resource base for competitive power production as well as making advanced drilling technology available to a host of other industries (see Box 6.3).**

- **Enhance R&D on reservoir diagnostics and modeling to better understand geothermal reservoir behavior, increase performance (productivity and system lifetime), and lower development costs.**

Funding levels within the geothermal program should be increased from $30 million in FY97 to $52 million. The increment should include funding at a level of up to about $5 million per year, with matching funding from ER, directed towards fundamental research needs in identifying and exploiting advanced geothermal energy technologies. This fundamental research should be both cofunded and comanaged by the geothermal program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

[40] Armstead et al. (1987), Tester et al. (1989).

Box 6.3: A Vision for Energy and Urban Infrastructure:
The National Advanced Drilling and Excavation Technology (NADET) Program

The National Advanced Drilling and Excavation Technologies (NADET) program promotes and facilitates collaborative crosscutting R&D on advanced rock penetration and removal methods to lower costs substantially and reduce the environmental impacts associated with underground engineering operations. Current expenditures are enormous—drilling operations worldwide are roughly $200 million per day; in North America they are $100 million per day; for mining and earth excavation operations worldwide they are in the hundreds of billions of dollars per year. Thus, the potential for cost savings by providing enabling new technologies is substantial and could have an enormous impact for both developed and developing countries. For example, if drilling costs could be reduced by 50 percent in general, lower-grade fossil and geothermal resources would become commercially competitive.

The NADET program was initiated in 1995 with seed funds provided by DOE's geothermal division. The NADET program provides a centralized, coordinated group that brings together energy, mining, and construction interests to share R&D directed at both evolutionary and revolutionary long-term opportunities to reduce costs. What is needed now is a means to provide multi-agency government support. The DOE, DOD, EPA, DOT, DOI, and others are all key stakeholders. About $20 million per year would be sufficient to engage the country's best talent in our universities and national laboratories, cost shared with the private sector, on an important set of problems. Critical opportunities exist in a number of areas such as (1) integrated smart drilling systems with look-ahead geophysical characterization methods; (2) hydraulically, thermally, and chemically assisted penetration methods to reduce or eliminate wear, and (3) drilling and tunnelling methods that form a protective casing as rock is removed to stabilize formations.

Hydropower

Hydropower is a relatively mature and competitive renewable energy technology with 92,000 MW installed capacity in the United States (74,000 MW conventional, 18,000 MW pumped storage). Currently, some 1200 hydropower plants generate approximately 10 percent of U.S. electricity and provide annual revenue in excess of $20 billion. In most cases, hydropower is also an integral part of multipurpose water management, such as flood control, irrigation, public water supplies, and recreational uses. There is the potential to install from 35,000 to 50,000 MW of new hydropower capacity in the United States, in large part using existing dam structures and reservoir systems. This approach avoids the potential environmental impacts associated with new dam structures, including land inundation, silting, and water quality.

Although hydropower emits little GHG,[41] a variety of environmental issues have been raised, including its impacts on water quality, river flows, and aquatic ecology (e.g., fish populations). For example, hydropower dams have been implicated in the decline of salmon populations in the Pacific Northwest. These environmental concerns have led to delays in Federal Energy Regulatory Commission relicensing of existing hydro facilities as well as in approving new facilities. On average, about 8 percent of existing hydro capacity is lost during relicensing as efforts are made to better regulate stream flows or address other problems. To maintain the existing U.S. hydro capacity, let alone expand it, a better understanding of the environmental impacts and tradeoffs, as well as ecological and technological R&D, are needed.

[41] Hydropower dams normally use large amounts of Portland-based cements which consume energy and generate carbon dioxide when it is manufactured; vegetation that is inundated when the reservoir is first filled can decay, producing methane.

Hydropower could play a particularly important role in a low-carbon energy future. Hydropower is dispatchable on very short notice and thus can provide load-following capability for intermittent renewable technologies such as solar and wind. Studies of system integration are needed, as is better understanding of the impact on aquatic ecology of ramping water flows up and down.

The worldwide potential for hydropower is very large, but low-cost fossil fuels, environmental concerns, and the capital intensity of major hydro installations will slow development Currently, there are 71 large-scale projects underway worldwide with plant capacities of 1000 MW or more. There is an opportunity for the United States to provide more efficient, more environmentally sustainable turbomachinery to a growing global market, but the United States has not been as aggressive as the Europeans with respect to R&D. Thus, it is likely that the United States will lose market share as a hydropower equipment provider. Most of the U.S. effort is directed toward managing engineering design and construction, not on developing new technology.

The DOE Hydropower Program, Assessment, and Recommendations

DOE support of hydropower technology R&D has been minimal in recent years—$1 million in FY1997.[42] This support is leveraged with about $3 million in funds from other agencies and from cost-sharing with private industry, through the National Hydropower Association, to focus on advanced turbine designs. In part, the low level of R&D support is a direct result of the maturity of the technology. Private utilities have not been funding much R&D; they have supported some projects focused on fish-related and water-quality problems, particularly with respect to evaluating the magnitude of the problem during relicensing, and, as such, are meeting regulatory demands rather than generating solutions. Overall, the DOE hydropower R&D program is seriously inadequate to address important environmental and technological concerns. Ecology-related projects are supported by individual agencies or organizations and are not well coordinated; considerable improvements in costs and effectiveness could result from better coordination of these efforts.

Hydropower is an important source of electricity for the U.S. and maintaining and strengthening this option is needed.

RD&D Recommendations for the DOE Hydropower Program include the following:

- **Accelerate multiyear research on advanced "fish-friendly" high-efficiency turbine designs including prototype testing to evaluate new, more efficient concepts. Techniques like computational fluid dynamics can play an important role here.**

- **Implement a coordinated water management research program involving DOE, the Power Marketing Administrations, the Environmental Protection Agency, the U.S. Army Corps of Engineers, Bureau of Reclamation, and other government agencies to assess the long-term ecological impacts of existing dams and reservoirs and to develop suitable mitigation strategies to assist in sustaining and increasing U.S. hydropower capacity. This should be coordinated with Federal Energy Regulatory Commission procedures and regulations.**

[42] INEEL (1997), Rhinehart et al. (1997).

- **Improve quantitative understanding of the long-term environmental impacts of land inundation, sedimentation and silt buildup, changes in oxygenation, and other aquatic ecology impacts.**

- **Develop environmentally sustainable, low-head run-of-river technologies that would have inherently low impacts compared with higher head systems that impound large volumes of water and alter river flows.**

- **Develop a coordinated program to examine the benefits and costs of coupling hydropower to renewable energy storage needs.**

Funding should be increased over a five-year period to roughly $12 million per year to support key turbine technology development and demonstration in cost-shared industry-led R&D programs. This core funding should be used to catalyze cost-sharing and coordination of R&D with other water-related Federal agencies as well. Innovative ways to fund this R&D should also be explored, particularly by tapping the income generated by federally owned hydropower facilities.

Electrical Systems and Storage

DOE funding of electrical energy systems R&D has been minimal in other than generation and, more recently, end-use technologies. Industry, with DARPA support, pioneered electronic control for Transmission and Distribution (T&D) systems. More recently DOE has contributed significantly to high-temperature superconductivity applications in demonstrations of transmission, superconducting magnetic energy storage (SMES) and power quality applications. In recent years DOE has joined the Electric Power Research Institute (EPRI) in supporting electromagnetic field (EMF) health effects research as well as energy storage R&D. DOE's total 1997 funding in these areas is $31.8 million with $20 million going to high-temperature superconductivity applications, $8 million to EMF, and $4 million to storage. T&D receives no support as it is viewed largely as a mature technology adequately funded by EPRI, utilities, and manufacturers, although there are new challenges (see Box 6.4).

Restructuring of the electricity industries will create considerable uncertainty for all emerging sectors, including generation, T&D, and public goods R&D largely funded by EPRI. Cost pressures will likely result in decreased R&D until utilities better define their future roles in the energy business. Storage technologies will offer benefits both upstream and downstream of the T&D system, which should eventually motivate more industry R&D once survivors in these highly competitive businesses emerge. Higher risk, long range and environmental research will rely largely on public sector support to leverage industry contributors through EPRI and other industry-funded programs. The National Cancer Institute (NCI) EMF study results just released showed no relationship with childhood cancer, and NCI recommends that future funding focus on more likely causes than EMF.

Storage will take on added importance in the future to ensure reliable, high-quality service. It will provide for increased renewable use and system stabilization with distributed generation. Areas of importance include pumped hydro, compressed air, battery, inertial, and SMES technologies covering a wide capacity range.[43] Industry-government collaboration is important in ensuring optimal program definition and utilization.

[43] Schainker (1997).

Box 6.4: Wires—Society's Lifeline

The U.S. population is literally wired together. These connections also serve parts of Canada and Mexico and are being extended both within countries and across borders. High-voltage transmission lines efficiently move power from remote, large power stations to urban areas where the voltage is stepped down to customer levels, 110 to 220 volts in homes and higher for commercial and industrial customers. The wires network permits efficient environmentally responsive use of a large versatile mix of generating plants scattered across the country. Economic, and more recently environmental, dispatch permits lowest electricity costs consistent with available plant and fuel mix at the world's highest reliability.

So what R&D is needed in the wires business? Research opportunities exist to increase reliability, efficiency, capacity, and control of the T&D system while reducing costs and environmental conflicts. Superconductivity and electrochemistry, smart thyristors, sensors and controllers as well as advances in boring, trenching and heat removal systems all afford opportunities to improve electrical services.

Reliability of the delivery system is by far the highest priority; it is growing in importance as electronic devices and automated production lines (which are much more sensitive to small voltage or frequency disturbance) become increasingly common and costly. Outages can affect a computer, a city, or several states depending on cause, location, and propagation. They can be caused by lightning, a customer induced disruption, a downed line or a flashover from an untrimmed tree. Undergrounding, if done at acceptable costs, could yield enormous benefits. Boring and trenching technology builds on advances in oil and gas drilling, and better heat removal systems from underground cable can improve reliability and reduce costs. Undergrounding offers significant environmental benefits as well, including eliminating visual impact and noise, and lowering EMF. Cost is the key, but the opportunities deserve attention.

High-temperature superconductivity (HTS) offers the possibility of increasing line capacity significantly and going underground in congested areas. Undergrounding advancements would aid in the overall economics of this technology as well. HTS SMES devices offer protection against short disturbances due to voltage, current, or harmonic irregularities. Advanced batteries also offer system support for improved power quality as well as storage for intermittent renewables. Other central station resources benefit by virtue of being able to use large transmission lines at higher capacity during off-peak periods.

"Smart" thyristors at high power levels represent an excellent example of industry and government collaboration. DARPA and EPRI cofunded an effort to build a computer control capability into a large power thyristor that permits control of electron flow on AC networks. Known as FACT—Flexible AC Transmissions, it is now being demonstrated in several systems. Further development could enhance the use of this technology to permit sufficient control capability to sustain reliable service at higher loadings.

Technology's potential to increase operational and economic efficiency, and environmental compatibility is large. Ownership and operational control will largely determine where the incentive for investing in R&D resides for transmission and/or distribution. Regulation of the wires is anticipated, and it is reasonable to presume that the regulatory process would allow recovery for R&D expenses as has been the practice. The ability to control flows more precisely than has been possible will add value to certain paths, but uncertainty in the recovery of cost is complicating investment priorities of present owners.

DOE should increase its scientific and technical capabilities in this area to ensure that national interests, particularly economic and reliability, are not compromised by indecision during the coming restructuring and reorientation of interests. Government should seek to provide incentives to corporate entities with ownership and operational responsibilities for electricity and gas transmission and distribution systems to engage in R&D that improves system performance and reduces costs.

Compressed-air energy storage in particular is well suited for use in both increasing the value of wind power and in making possible high levels of penetration of wind power on electric grids. The technology is commercially available and has been demonstrated with storage in solution-mined caverns in bedded salt. It should also be demonstrated for storage in porous media and in conventionally mined hard rock caverns. Advanced turbomachinery concepts and technologies should also be demonstrated; lower capital costs can be realized from use of saturated/humidified air in the cycle and more modern expansion turbines with higher turbine inlet temperatures.[44]

Superconducting transmission technology has progressed to the point where a 1.5 kilometer demonstration project has been proposed for industry-government support. Given the potential for this technology to relieve congestion on segments of transmission in urban areas, it should get continued support from DOE for the first-of-a-kind deployment.

Attention must be given to the implications of competition on the delivery system in terms of reliability, stability, and power quality. Outages will have increasingly significant economic impacts, and the public interest will be served by R&D investments to ensure that outages are minimized in both frequency and scope.

Industry involvement in defining issues, opportunities, and priorities is essential to responsive R&D and rapid application of results. EPRI, as one example, provides the connection with industry expertise, funding and rapid results dissemination. Other similar and varied approaches to involving industry in government-funded R&D exist and need to be "mined" to ensure that best practices are used in the future.

Budget Recommendation

The Panel recommends that funding for EMF effects be terminated, as planned; that energy storage R&D be increased from the FY1997 of $4 million to a 2003 level of $12 million; that R&D on Transmission and Distribution technologies be increased from the FY1997 level of $0 to $10 million in FY2003, and that superconductivity R&D should be raised from the FY1997 level of $19.75 million to $36 million.

Biomass Energy

Biomass energy, the chemical energy stored in organic plant matter and derived from solar energy via photosynthesis, accounted for 3 percent of total U.S. energy in 1995. Major activities include power generation from 7.6 gigawatts of installed biomass steam-electric capacity and the production of about 1 billion gallons per year of ethanol from corn. Biomass electricity is produced at low (~ 20 percent) efficiencies in small, relatively capital-intensive, sometimes polluting power plants, in which electricity can be produced cost-effectively using low-cost biomass residues of the forest product and agricultural industries. However, there is little opportunity to expand biopower capacity with current technology because supplies of low-cost residues are limited. And there is little prospect that ethanol derived from corn can be provided without Federal subsidy, which is currently 54 cents per gallon. However, prospects are good that biomass could play major energy roles using advanced conversion and end-use technologies.

[44] Schainker (1993, 1997).

Environmental Issues

When biomass is grown at the rate it is used for energy, there are no net CO_2 emissions from the biomass; life-cycle CO_2 emissions (associated mainly with fossil fuel use for biomass growing, harvesting, transport, and processing) can be relatively high for options with poor economic prospects (e.g., corn-derived ethanol) but are generally low for options with good economic prospects (e.g., ethanol derived from cellulosic feedstocks).

When perennial grasses or short rotation woody crops (SRWCs) are grown as energy crops on excess agricultural lands the local environment can be improved relative to prior land use growing annual row food crops. Such energy crops, well managed, can help control erosion, can act as filters to reduce runoff of agricultural chemicals, and can offer better wildlife protection—with energy croplands potentially serving directly as habitat or as buffers around, or corridors between, fragments of natural habitat. But environmental conditions would improve even more if excess croplands were instead converted into natural wildlife habitat. Likewise, conversion of natural habitat to the production of biomass energy crops would harm local habitat.

Air pollutant emissions in conversion to useful energy forms and energy services depend on the conversion technologies involved, except that biomass conversion is generally characterized by very low SO_2 emissions, owing to the low sulfur content of biomass. Gasification-based power-generating technologies now under development will have low emissions of all local pollutants, except in some cases NO_x emissions arising from fuel-bound nitrogen, which might require the use of emission control equipment. Ethanol blends with gasoline in internal combustion engine vehicles are not expected to provide air quality benefits in excess of what can be provided by reformulated gasoline, and neat ethanol used in internal combustion engine cars would be only marginally better. But dramatic reductions in local air-pollutant emissions relative to gasoline internal combustion engine cars would probably be realizable with alcohol-powered fuel cell cars, and air pollutant emissions would be zero for fuel cell cars powered by biomass-derived hydrogen.

Other Attractions of Bioenergy

Growing biomass for energy on excess agricultural lands would increase farm income and reduce crop risk while decreasing the need for Federal farm income support programs. Farm income support is a major Federal budget obligation: deficiency payments for commodity crop production averaged $5.5 billion per year, 1990 to 1995, and the total cost of farm support programs (including the Conservation Reserve Program—CRP—currently costing about $1.4 billion per year, and other environmental protection programs, and various disaster insurance programs for crops) has been about $10 billion per year in recent years. The costs of many of these programs could be reduced by growing appropriate energy crops. For example, energy crops such as perennial grasses or SRWCs could be used for erosion control as an alternative to part of the CRP; the growing of flood-resistant trees on floodplains could reduce the loss of food crops to flooding and the need for flood insurance; and the growing of energy crops on otherwise idled lands would reduce the need for farm income support programs.

Biomass transport fuel production could also reduce dependence on oil imports, especially from insecure sources. The U.S. oil import bill rose from $45 billion in 1994 (30 percent of net imports) to $64 billion in 1996 (38 percent of net imports) and is projected to increase to the $100 billion range by 2015; moreover, the Persian Gulf share of oil exports is now more than 50 percent and is expected to exceed 70 percent by 2015.

Modernized biomass energy could also stimulate rural development in developing countries, where biomass supplies are often widely available and potential markets huge: some two billion people live in rural areas of developing countries without access to grid electricity.

Because of multiple potential benefits there is growing interest in expanding biomass use for energy in new ways, especially for power generation and production of transportation fuels, the major foci of the DOE bioenergy programs. Initially this expansion would be based mainly on the use of residues; but over the longer term biomass energy crops (mainly perennial grasses and SRWCs) would also contribute. The Shell International Petroleum Company has projected that by 2050 biomass could contribute to global energy the equivalent of 40 to 50 percent of present energy.[45] Moreover, in its Second Assessment Report, the Intergovernmental Panel on Climate Change identified biomass as potentially being able to contribute by 2050 the equivalent of 25 to 45 percent of present global energy.[46] Such projections are inspired by the multiple potential environmental and economic benefits and prospectively favorable costs of modern bioenergy technologies.

The DOE Program

The program is divided into Biopower and Biofuels sub-programs. Biopower activities are relatively new (launched in 1992) while the Biofuels activities are well-established (launched in 1978). Feedstock development is supported with funds from both sub-programs ($2.5 million from Biofuels and $2.0 million from biopower in FY 1997).

<u>Biopower</u>. Modest R&D support is being provided to industry in support of cofiring fossil fuel power plants with biomass residues, as a near-term strategy to help launch a biomass fuel infrastructure while providing some near-term GHG emissions reduction benefits.

The program's focus is on integrating biomass gasifiers with gas-turbine-based power systems [biomass integrated gasifier/combined cycle (BIGCC) plants], building on advances already made for coal. With adequate R&D support, technology transfer from coal to biomass could come quickly, because biomass has advantages over coal; it has a low sulfur content, and it is more reactive and thus easier to gasify. Efficiencies of 35 to 40 percent are expected for first generation BIGCC plants using commercial gas turbines and of the order of 45 percent with advanced gas turbines being developed under the Advanced Turbine Systems (ATS) program at Fossil Energy (FE) and EERE.

Efficiencies as high as 60 percent are possible with advanced biomass integrated gasification/fuel cell (BIGFC) power plants (based on molten carbonate or solid oxide fuel cells), which could also involve gas turbine and/or steam turbine bottoming cycles. Molten carbonate and solid oxide fuel cells, being developed in FE for natural gas applications, are not yet in the biopower portfolio.

Program managers hope to launch a modular-scale systems initiative, targeting applications at scales ranging from tens of kilowatts up to a few megawatts, with technologies such as integrated gasifier/Stirling engine and integrated gasifier/solid oxide fuel cell/micro gas turbine systems. Both high efficiencies (40 to 60 percent) and, in mass production, low specific capital costs might be achievable with some of these systems.

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[45] Kassler (1992), Shell (1995).
[46] IPCC (1996).

Biofuels. The program is focused on ethanol production from low-cost cellulosic materials (e.g., various residues in the near term and also energy crops in the longer term) via enzymatic hydrolysis. The challenge is to find cost-effective ways to convert the cellulose and hemicellulose in these feedstocks into component sugars via hydrolysis and then ferment those sugars to ethanol. Unlike the situation with corn-derived ethanol there are good prospects for making this technology fully competitive with petroleum in transport markets using advanced technology. Domestic production goals for ethanol derived via enzymatic hydrolysis are 2.4, 8, 16, and 19 billion gallons by 2005, 2010, 2020, and 2030, respectively. The program's market strategy is to launch the technology in high-value niche markets where it would be used as an oxygenate or octane-boosting additive to gasoline until about 2015, and, thereafter, also as a neat fuel. The program has made major advances: As a result of the R&D, the estimated cost of producing ethanol from woody feedstocks has been reduced from $4.6 per gallon in 1980 to about $1.2 per gallon today. Yet ethanol is still not competitive. For example, the value of ethanol is $0.70-$1.00 per gallon as an oxygenate, and about $0.60 per gallon and $0.50 per gallon as a neat fuel competing with gasoline in optimized internal combustion engine and fuel cell cars, respectively, when the refinery-gate gasoline price is $0.75 per gallon (it averaged $0.71 per gallon in 1996). Production cost goals with R&D support in the range $28 to $32 million per year (2000 to 2030) are $0.79, $0.67, and $0.60, and $0.56 per gallon, by 2005, 2010, 2020, and 2030, respectively.

Feedstocks. Feedstock R&D, focused on the development of dedicated energy crops, is key to the ultimate successes of the biopower and biofuels programs, because in the long run biomass can play major roles in the energy economy only if residue supplies are supplemented by biomass grown as dedicated energy crops. Since the effort was launched in 1980, more than 100 woody species and 25 grassy species have been examined for their suitability as energy crops. Six species of woody crops and one grassy crop were selected as models for intensive development. However, because of budget constraints, ongoing development is limited to two SRWCs (hybrid poplar and willow) and one perennial grass (switchgrass). Since 1980 advances in breeding techniques and genetic engineering have made possible rapid improvements in crop productivity. Biomass yields have increased 50 percent or more and costs have been declining substantially for the two principal crops: hybrid poplar and switchgrass. Methods of establishing and maintaining these crops have also been developed and improved.

Constraints on Biomass Energy

Biomass can be only a partial solution to the global energy problem because of two fundamental constraints: its high water requirements and the inherent low photosynthetic efficiency of converting solar energy into the chemical energy of plant matter. High water requirements constrain biomass production mainly to regions where rainfall is adequate to support commercial yields, whereas the low photosynthetic efficiency can lead to land-use competition, e.g., with food production. In addition, there may be practical constraints relating to costs for biomass energy crops. There are good prospects that biopower systems will be able to compete with much larger coal power systems in terms of capital cost—both because of the physical advantages offered by biomass and the potential for economies of mass production, offsetting the economies of scale that are feasible with coal. However, for plantation biomass, feedstock costs will be higher than for coal in many parts of the United States, even if the DOE goals for plantation biomass cost reduction are met.

Despite such constraints biomass can still play major roles. The fundamental constraints can be countered by emphasizing energy-efficient technologies for biomass conversion and end-use. The practical constraint relating to prospective biomass production costs can be dealt with by emphasizing coproduct biomass feedstock strategies (e.g. producing some combination of biomass chemicals, fibers, fuels, heat, and electricity at the same time to maximize economic value). Such possibilities are illustrated by the thought experiment presented in Box 6.5.

Box 6.5: Alternative Ways To Use 5 ExaJoules of Biomass per Year—A Thought Experiment

Consider alternative scenarios for using 5 ExaJoules of biomass per year (4.7 quads per year, equivalent to 5 percent of U.S. energy in 1995) to make ethanol from the carbohydrate fraction of the biomass as a gasoline substitute and electricity from the lignin as a substitute for coal electricity, in the context of an energy system having the same CO_2 emissions and using as much coal and oil for power plants and cars and light trucks (i.e., light-duty vehicles—LDVs) as the United States in 1995. This much biomass could be available at attractive costs by 2015; somewhat more than half would come from agricultural residues and the rest from energy crops grown on 7.3 million hectares (18 million acres). With this modest level of land required for energy crops (equivalent to half the area authorized for the CRP in any year) competition with food production is likely to be very modest.

In the first scenario, 31 billion gallons of ethanol are produced and by-product electricity is cogenerated in conventional steam plants, providing 12 gigawatts of export power. The ethanol is used as a neat fuel in LDVs with internal combustion engines optimized to run on ethanol (so that the gasoline-equivalent fuel economy is 24 mpg, compared to the actual average of 19.5 mpg in 1995) but otherwise identical to LDVs used in 1995. Gasoline requirements for LDVs and coal requirements for power are reduced 22 percent and 6 percent, respectively; oil imports are reduced $10 billion per year; and U.S. CO_2 emissions are reduced 6 percent.

In the second scenario, 28 billion gallons of ethanol are produced, but by-product electricity is cogenerated in energy-efficient molten carbonate fuel cell-based power plants that provide 36 gigawatts of export power. The ethanol is used in fuel cell vehicles having load characteristics (reduced weight, reduced aerodynamic drag, reduced rolling resistance, etc.) similar to those targeted for the car of the future under the Partnership for a New Generation of Vehicles (PNGV, see Chapter 3) and an estimated gasoline-equivalent fuel economy of 71 mpg. In this scenario, gasoline and coal requirements are reduced 61 percent and 17 percent, respectively; oil imports are reduced $29 billion per year; and U.S. CO_2 emissions are reduced 20 percent.

Evaluation and Recommendations for R&D

The program has many strong features. The major shortcomings are that the programs are substantially underfunded and not ambitious enough with regard to longer-term R&D.

There is an urgency to have in place much stronger programs with good links to the U.S. Department of Agriculture by 2000 to 2002, the period when the next farm bill will be enacted. The prospects of reducing agricultural support payments substantially in the next farm bill will be enhanced if the farmer then sees good prospects for earning income by planting energy crops on excess croplands. For the reasons articulated below, **it is recommended that the Bioenergy budget be increased from the FY 1997 level to some $192 million per year, allocated to biofuels, biopower, and feedstock R&D, respectively (see Table 6-1).** Although the recommended $136 million per year increase seems large, it is just 1 percent of the $10 billion per year the taxpayer commits to agricultural support programs and should be considered a bargain even if the only benefit that could be derived from this investment were the reduced need for agricultural support programs as a result of creating new productive uses for agricultural land.

For biopower, the focus should be on medium- and long-term activities. For BIGCC technology, the program has the right priorities. The major technological challenges, gas cleanup to gas turbine quality and feedstock feeders for pressurized gasifiers, are being addressed. To solve these problems, **collaborations should also be considered with Scandinavian developers, who have considerable experience with biomass gasifiers for gas turbine applications. The program needs**

substantial new support to take the next steps toward commercialization with demonstration projects, including demonstrations with appropriate advanced turbines developed under the ATS program. A substantial and diversified new initiative should be launched in the area of small-scale technologies, which could help promote rural development in sustainable ways, especially in developing countries, where the potential market is huge. This is also an area where international collaborative R&D is needed to enhance the prospects that technologies developed are appropriately tailored to local needs.

For biofuels, more ambitious technology advancement and cost-reduction targets should be set for the production of ethanol via enzymatic hydrolysis. The program should be put on a course such that there are good prospects of reaching by 2010 to 2015 an ethanol price of $0.50 per gallon, which would make ethanol widely competitive as a gasoline substitute. So doing would require a substantially expanded core R&D effort. Core R&D should account for about half of the total recommended budget for biofuels and be sustained at that level for at least 5 years. Emphasis should be given to advanced biomass pretreatment (e.g., liquid hot water pretreatment) to facilitate enzymatic hydrolysis and to consolidated bioprocessing, which refers to achieving the production of cellulase (the enzyme used to hydrolyze cellulose), cellulose hydrolysis, and both hexose and pentose fermentation in one process step. There should also be a substantial fundamental research effort in the Program aimed at developing a fundamental understanding of cellulase and hemicellulase enzyme systems (both naturally occurring and recombinant), as well as the microorganisms that produce them, the structure and hydrolysis of biomass substrates (including pretreated substrates), and the chemical reaction mechanisms occurring during biomass pretreatment. This effort should be supported at a level of up to about $5 million per year, with matching funding from ER. This fundamental research should be both cofunded and comanaged by the biofuels program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

A strong technical case has been made that, with an aggressive pursuit of core technology development, such cost levels could be achievable in large plants.[47] DOE should pursue such a course in part out of consideration that air quality is a major public concern. As noted, use in fuel-cell vehicles offers the best prospects for improving urban air quality with ethanol as a transport fuel. If there is a PNGV-2, as recommended in Chapter 3, fuel cell cars might begin to enter the market by 2008. For ethanol to compete with gasoline in such cars, a production cost of about $0.50 per gallon would probably be necessary. Fuel-cell cars would also enable biomass-derived ethanol to play major roles in transportation in a global future where land-use constraints limit supply availability, as noted earlier.

There should be a strong collaboration between the Biofuels and Biopower programs aimed at identifying and developing the optimal power-generating technologies for the coproduction of ethanol from the carbohydrate fractions and electricity from lignin.[48] As shown by the thought experiment (Box 6.5), the ethanol industry could become a major power exporter using advanced fuel-cell-based power systems; such power systems are likely to be highly competitive with fossil fuel electricity even when dedicated energy crops are used, because of the high and effective rate of utilization of the entire biomass feedstock.

The biofuels program should also reestablish a modest program on thermochemical conversion technology for biomass based on gasification, with funding rising to a level of about $5 million per year by 2001. Thermochemical gasification technologies that produce synthesis gas (a gaseous mixture consisting mostly of CO and H_2) as an intermediary product are needed. The

[47] Lynd et al. (1996).
[48] Casten et al. (1997).

emphasis should be on hydrogen production from biomass. In the long term, biomass-derived hydrogen could be an alternative to ethanol with onboard conversion to hydrogen for fuel cell vehicle applications. Development of biomass gasification technology for H_2 production would provide the flexibility to use biomass in the production of a wide range of fuels that can be derived from synthesis gas (e.g., methanol, Fischer-Tropsch liquids, and dimethyl ether), as well as various synthesis gas-derived chemicals such as ammonia. Such flexibility is desirable in light of the fact that fossil fuel-based synthetic fuel technology is evolving along these lines (see Chapter 4). **This effort should also be closely coordinated with the biopower program, exploiting opportunities for developing those gasification technologies that can serve needs of both the biofuels program and the biopower program.**

Although the feedstock R&D program has done well on a limited budget, the activity should be substantially expanded, to about $15 million per year total (with equal contributions from the Biofuels and the Biopower programs) both to make possible major roles for biomass in the energy economy and to deal effectively with environmental and land-use competition issues. R&D priorities include: (1) breeding and genetic engineering strategies for developing faster-growing energy crop varieties that require minimal nutrient and water inputs; (2) diversification of the portfolio of feedstocks; (3) field studies on relatively large-scale plantation sites aimed at better understanding lifecycle impacts; (4) development of biodiversity management strategies; (5) polycultural development strategies; (6) studies of land-use competition and development of approaches for minimizing competition in environmentally sound ways; and (7) international collaborative field research, on a world region-by-region basis, aimed at developing technical strategies for restoring degraded lands so that they can be used productively and sustainably for the growing of biomass for energy. The program should initiate, in collaboration with ER, fundamental research on perennial species of energy crops; research is needed in areas such as nitrogen fixation, carbon allocation, including genetic and hormonal controls, photosynthesis, respiration, and metabolic exchanges between photosynthesis and respiration. This research should be funded with funding up to $2 million from the biomass feedstock program plus matching funds from ER. This program should be both cofunded and comanaged by the biomass feedstock R&D program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

Recommendations Relating to Commercialization

Successful R&D and demonstration projects must be linked to commercialization strategies that involve risk-sharing strategies for buying down the cost of the initial plants. As discussed at the beginning of this chapter and in more detail in Chapter 7, limited Federal government support for commercialization activities can often be justified, especially for technologies that offer strong public as well as private benefits. There are unique opportunities for pursuing innovative commercialization programs for biomass energy.

The pulp and paper industry has a strong interest in integrated gasification/combined cycle technologies for both residual biomass (hog fuel) and black liquor. There is a unique opportunity to engage this industry in the commercialization of these technologies, because it will have to replace or refurbish a large fraction of its boiler capacity over the next 15 to 20 years; integrated gasification combined cycle technology offers the promise of being more environmentally and economically attractive than introducing replacement capacity based on existing technology. If integrated gasification/combined cycle technology were the technology of choice for this activity, the chemical pulp and paper industry could rely wholly on renewable energy and export 15 gigawatts of biopower to utility grids by 2020.[49] **The DOE should both**

[49] Larson et al. (1997).

engage the industry in demonstration projects for these technologies and work with the industry to find efficient and effective risk-sharing strategies for buying down the costs of the initial plants that would be purchased after successful demonstration.

Technology for producing ethanol from cellulosic feedstocks has advanced to where commercial plants can be built for which the ethanol would probably be competitive in niche market applications based on the use of low-cost biomass waste feedstocks. There is a near-term opportunity to carry out this commercialization activity in conjunction with a phasing out of the subsidies for corn-based ethanol, which has poor long-term economic prospects. The current Federal tax credit for ethanol, which costs the U.S. Treasury about $750 million per year, is scheduled to expire in 2000. Although a precipitous elimination of this tax credit would undermine efforts to commercialize advanced technology by eliminating the ethanol market, long-term extension of the credit in its current form would probably encourage continuation of business-as-usual corn-to-ethanol production. At least four companies are currently trying to secure private financing to build their first commercial plants to produce ethanol from low-cost waste streams. An example of a policy change that would facilitate a transition to new technology is to phase out the existing credit (2000 to 2005), while simultaneously phasing in a temporary performance-based credit that would distribute available resources (capped at a total of $750 million) to ethanol producers based on the full fuel-cycle GHG emission reductions achieved by each particular producer.

Hydrogen

In the twenty-first century hydrogen might become an energy carrier of importance comparable to electricity. This is a very important mid- to long-term research area.

Hydrogen and the Low-Temperature Fuel Cell

Hydrogen, like electricity, is a high-quality but high-cost energy carrier. Its adoption by the market depends on the availability of technologies and/or policies that put a high market value on H_2. One such enabling technology for H_2 is the low-temperature fuel cell (FC), which has wide market opportunities in both transportation and stationary combined heat and power (CHP) applications. Currently the most promising low-temperature FC is the proton-exchange membrane (PEM) FC, a focus of DOE and industrial R&D efforts. The PEM fuel cell offers the potential of low cost in mass production and power densities high enough even for demanding applications such as the automobile (see Chapter 3).

The successful commercialization of the low temperature FC would put a high market price on H_2 because H_2 is the natural fuel for low-temperature FCs. However, the fuel delivered to a FC can also be some other fuel that is processed at the point of use into a H_2-rich gas the FC can use. Because there is no H_2 energy infrastructure, PEM FCs might be launched in the market with conventional hydrocarbon fuels and point-of-use fuel processors. For CHP applications PEM FCs will be fueled initially with natural gas (NG) that is reformed onsite to a H_2-rich gaseous mixture the FC can utilize; fuel processors for such applications are commercially available. For automotive applications, projects supported by the Office of Transportation Technologies (OTT) in EE and industrial R&D efforts in the United States and abroad are directed to developing fuel processors that could convert onboard the vehicle a liquid fuel (e.g., gasoline, diesel fuel, a synthetic hydrocarbon fuel, methanol or ethanol) into a suitable H_2-rich gas.

If FCs are launched in the market this way, there would be strong market pressures to shift to H_2 as quickly as a H_2 infrastructure could be put into place. PEM FCs operate at such low temperatures (~80 C) that fuel processing at the point of use to produce a H_2-rich gas suitable for FC use is relatively inefficient. And gasoline FC cars would be heavier, less energy-efficient, and more costly to own and operate (e.g. on a cents per km basis) than FC cars operated on H_2 derived from natural gas, even though the H_2 would be more costly (on a \$/GJ basis) in the latter case.

Prospective Benefits of H_2

H_2 FCs emit no air pollutants and could be supported with domestic energy sources, reducing oil imports. Zero life-cycle CO_2 emissions can be realized if H_2 is produced electrolytically from water using renewable power sources. When H_2 is produced from fossil fuels, deep reductions in CO_2 emissions can be achieved by sequestering the CO_2 separated from H_2 at the production facility.

H_2 Production

About 1 percent of U.S. primary energy is used to produce H_2, mostly for chemical process industry use. Most H_2 is produced from natural gas, the least costly approach and a mature technology; about 5 percent of U.S. natural gas production is used to make H_2.

H_2 can also be derived from any other carbonaceous feedstock (e.g., heavy oil, coal, biomass, municipal solid waste) via thermochemical gasification. When H_2 is produced from a carbonaceous feedstock a stream of nearly pure CO_2 (accounting for two-thirds or more of the carbon in the feedstock) can be produced as a byproduct and isolated from the atmosphere [e.g., through sequestration (storage) underground in depleted oil or gas fields, deep coal beds, or deep saline aquifers, and possibly also in the deep ocean], potentially at low incremental cost. Because underground storage capacity for CO_2 is probably at least several hundreds and possibly thousands of gigatons of carbon (GtC), successful development of low-temperature FCs would make possible major roles for fossil fuels in a GHG-constrained world.[50] Except for market applications in which H_2 is produced from offpeak hydropower or other low-cost surplus electricity, electrolytic hydrogen will be much more costly than H_2 produced from carbonaceous feedstocks, even if CO_2 sequestration costs are taken into account and long-term cost goals for renewable electric sources are met.

The DOE Program

H_2-producing and H_2-using technologies, various enabling technologies (e.g., H_2 storage), and systems analysis are currently supported. While the program was small (\$1 to \$2 million per year) in the 1980s, it has recently grown to its current funding level of \$15 million per year.

Assessment

The DOE program has several good projects addressing critical needs, such as H_2 storage (notably light-weight storage canisters for storing H_2 at high pressures and carbon nanostructure storage); sorption-enhanced reactions for H_2 production; gaseous separation technologies; R&D on and novel demonstrations of fuel cells; H_2 diagnostics; H_2 safety research; and systems analysis.

Also included in the Program, however, are some projects of questionable merit.. For example, the program includes development and demonstrations of H_2 internal combustion engine (ICE) vehicles—technologies that have poor market prospects, as they will not be able to compete with ICE vehicles fired with natural gas, the feedstock from which most H_2 will be derived in the decades ahead. These activities should be phased out.

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[50] Socolow (1997).

In contrast, R&D involving enabling technologies and infrastructure-building activities relating to H_2 FC vehicles are appropriate. The program should collaborate with ER in the development of advanced H_2 storage technologies (e.g., various approaches using carbon nanostructure materials). Program activities should be closely coordinated with and supportive of the fuel cell combined heat and power activities of the Office of Building Technologies (OBE) in EE and of the PNGV-2 activities proposed in Chapter 3 for the OTT in EE. The program should consider supporting, in partnership with appropriate state and city agencies, demonstrations of near-term H_2 FC applications such as urban transit buses and residential/commercial CHP coupled to decentralized but offsite H_2 production (e.g., with recently developed small-scale systems for making H_2 from natural gas).

Highest priority for H_2 production should be, in cooperation with FE, cooptimizing H_2 production from fossil fuels and sequestering the separated CO_2. Also important is H_2 production from municipal solid waste and biomass through thermochemical gasification, which produces synthesis gas (a gaseous mixture consisting mostly of CO and H_2) as an intermediary product. The hydrogen program has an embryonic effort related to the production of hydrogen from municipal solid waste. This effort should evolve in close cooperation with the thermochemical fuels production effort (which will emphasize hydrogen production from biomass) that the Energy R&D Panel recommended be established in the biofuels program. This collaboration should explore possible synergies, such as in the choice of gasifiers that might accommodate both biomass and municipal solid waste feedstocks.

Another important renewable energy option is solar thermal energy-assisted production of H_2 from natural gas. The program should pursue this technology in collaboration with the STE program at EERE, with FE, and with foreign groups that have active programs for the required high-temperature solar receivers. Electrolytic R&D should be directed to developing systems (e.g., low-cost electrolyzers or reversible fuel cells) that can be operated cost-effectively at low capacity factors using offpeak hydropower or other low-cost surplus electricity supplies. Long-term R&D on H_2 production via photobiological processes (e.g., via photosynthetic bacteria, cyanobacteria, and green algae) and photoelectrochemical processes (using photovoltaic semiconductor technology to produce H_2 and O_2 via electrolysis without the intermediary step of first producing electricity) should be sustained at modest support levels; these are both high-risk options.

International collaborative R&D should also be pursued on H_2 FC vehicular applications to developing countries, where transportation demand, associated oil requirements, and air pollution are growing rapidly. Emphasis should be given to transport modes that are both important in developing countries and suitable for FC use—including buses, two- and three-wheel vehicles, and locomotives.

Recommendations

The H_2 program needs better articulated near-, medium-, and long-term goals. Systems analyses assessing alternative evolutionary strategies for the development of an H_2 economy that are continually updated in light of new knowledge could be especially helpful to management in its articulation and periodic updating of these goals. Since many of the important opportunities cut across all major divisions of the DOE (ER and FE as well as EERE), goal articulation should be carried out in collaboration with appropriate experts from the other DOE divisions, with coordination from top DOE management. The program should be reprioritized within the context of the present budget level along the lines recommended here and substantially expanded to about twice its present level by 2003, with the additional roughly $15 million of support coming in about equal shares from FE (for R&D on advanced technologies for H_2 production from fossil fuels and related

infrastructure development), from the proposed biofuels effort relating to thermochemically derived fuels production, and from ER (for fundamental research relating to advanced H_2 storage and other issues). The fundamental research should be both cofunded and comanaged by the hydrogen program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

Solar Buildings

Buildings account for one-third of total energy use and two-thirds of all electricity use, with commercial buildings consuming roughly 40 percent and residential buildings 60 percent of this total. Detailed monitoring of buildings in the United States and other Organization for Economic Cooperation and Development countries has shown that energy use can cost-effectively be cut in half using commercially available energy efficiency and passive renewable design features and efficient equipment. Substantial further gains are possible, and buildings that require no net energy inputs are an appropriate goal for the DOE program (see also Chapter 3: Efficiency).

Energy-efficient and passive solar architecture—which require few or no additional materials—are the most cost-effective of the building renewable energy technologies.[51] Passive architecture uses the same elements as the conventional building—for example, walls, windows, overhangs—but reconfigures them to capture, store, and distribute renewable energy. Energy-efficient building shells are an important part of this, and, although they are necessarily "tight," indoor air quality can be maintained with air-to-air heat exchangers. Daylighting is a technique for emphasizing the use of natural light and integrating it with artificial light as necessary, using advanced lighting controls. All buildings use some daylighting, but in conventional buildings it is often too intense, it creates glare, and it requires shades; daylighting techniques make this light useable. Building-integrated (active) technologies that reduce material use by serving both as part of the roof or wall and as an energy collector are also frequently cost-effective. In contrast, add-on technologies—such as separate rooftop collectors to provide low-quality heat, the type most people think of—require substantial additional and often expensive materials. To be cost-effective, such systems must minimize the cost of materials while still achieving relatively high performance and long lifetimes.

Progress and Prospects

The need for minimizing material costs poses substantial challenges and opportunities. The building-integrated photovoltaics research, for example, is developing thin-film PVs layered directly onto shingles or other roofing materials, wall materials, and even skylights—eliminating the module frame and support structure. The building itself becomes an electricity generator, significantly reducing generation costs. This technology received an R&D100 award last year and deserves stronger support. Further development of distributed utility technologies and analytical tools are important complements to this work. Similarly, researchers recently developed an innovative air-heating technology that cut costs of air heating by a factor of 5; this work also won an R&D100 award.

In contrast, domestic solar water heater technology has seen only modest gains and market penetration has largely stalled since the mid-1980s, when investment tax credits were withdrawn. Most of the funding in recent years has been directed at standards, market development, and technical support of the current technology. Although this is useful work, it does not adequately address the chicken-and-egg problem of high system costs limiting market penetration, resulting in low volumes and high production costs, and generating high marketing overheads. Manufacturers of solar water heaters are generally tiny

[51] OTA (1995).

operations; most consist of only a dozen or so employees and do not have the resources or expertise to do significant RD&D on innovative low-cost technologies or to substantially improve manufacturing process technologies that lower costs.

There are significant technical opportunities to reduce the cost of domestic solar water heating through innovative technologies. These include use of passive overheating protection mechanisms, the substitution of plastic or elastomer for metals in the collector and piping, thin-film polymer collectors, low-cost drainback systems, integral-collector storage systems, innovative glazing materials, PV/thermal hybrids, and others. This work depends on both substantially advancing system design and developing high-performance materials that can provide long lifetimes under difficult operating conditions. With domestic hot water alone accounting for a quarter of total residential natural gas use and 10 percent of residential electricity use, the development of low-cost solar domestic hot water technologies represents a major opportunity.

Increasing attention is being given to “whole building” strategies that consider all the building elements in an integrated manner, including the building envelope, heating/cooling, lighting, water heating, appliances, and human occupancy. Such strategies consider not just temperature, but also humidity, air flows and air exchange, radiant heat exchange, lighting, and other factors that determine comfort and productivity. A key element of such whole-building strategies is the development and widespread dissemination and use of advanced computer tools that take energy into account in the building design. Such computer design tools can also be used to track material flows, minimize construction wastes, and lower overall construction costs.

International Opportunities

International opportunities in buildings technologies are enormous. Urban populations in developing countries total roughly 1.65 billion and are increasing by roughly 60 million per year, with correspondingly massive investment in commercial and residential construction. The development of innovative technologies and design tools, and their application to buildings in developing countries offer a substantial market opportunity as well as potentially substantial impacts on reducing global carbon emissions. Advances in low-cost solar thermal systems can potentially also be applied to desalination, disinfection, crop drying, process heat, and other needs.

The DOE Program

The Solar Buildings Program within the DOE Office of Utility Technologies focuses on active solar thermal technologies for building space heating/cooling, water heating, and process heat, and on building-integrated PVs. The program was funded at $2.5 million in FY1997, down from $4.8 million in FY1994.

Recommendations

Research activities should be expanded in the following areas:

- **Energy efficient and passive architecture in the context of whole-building design.**

- **Building integrated renewable energy systems, including PVs and low cost thermal collectors.**

- **Low-cost solar water heater and other solar thermal collectors—materials, design, and manufacturing process technologies.**

- **Building design tools, including for energy design, materials flows, and other aspects.**

- **International building design and low-cost thermal systems.**

- **Advanced thermal storage materials, dynamic building materials, electrochromics, daylighting technologies and lighting controls, high-efficiency appliances, advanced sensors and controls, low-pressure and natural ventilation systems, moisture transport/adsorption/desorption and condensation, modeling of complex heat transfer in buildings, monitoring and model calibration methodologies, and system integration—including components, controls, and software, (see Chapter 3).**

The Solar Buildings Program should be integrated with other DOE building activities–including building shell R&D and appliance and lighting R&D.

Funding for these activities should be increased to $9 million total and the program activities should be closely integrated with those of the Office of Building Technologies. Also, fundamental research is needed on UV and temperature durable polymers, electrochromics, advanced thermal storage materials, and modeling complex heat and moisture transport in buildings. This research should be funded with funding up to $2.5 million from the solar buildings program plus matching funds from ER. This program should be both cofunded and comanaged by the solar buildings program and by ER in the manner and under the conditions described in the R&D management section of Chapter 7.

International

International use of renewable energy is important for several reasons. Developing countries benefit by using domestic resources in place of imports of high-cost energy resources; catalyzing economic development in rural areas through the installation of cost-effective renewable energy systems; and building a clean energy infrastructure that minimizes SOx, NOx, carbon, and other emissions—particularly in urban areas. The United States benefits by: reductions in pressure on world oil supplies, reductions in global carbon emissions, increases in economic growth and stability in developing countries, and by the opening of new markets for U.S. products.[52]

International markets are also critical for U.S. renewable energy companies. Some 82 percent of the global photovoltaics market, 99 percent of the wind turbine market, and large shares of the markets for biomass power, geothermal, and other renewable technologies are currently outside the United States—and these markets are growing rapidly. In contrast, the U.S. market for many renewable energy technologies is stagnant because of stiff competition from low-cost natural-gas-fired combined-cycle systems and looming electricity sector restructuring. For U.S. renewable energy companies to realize economies of scale in production and drive down costs, they must capture a fair share of these foreign markets. Failure to do so would stunt their growth compared to foreign competitors, and could ultimately leave the U.S. industry

[52] OTA (1995).

non-competitive. This may already be happening for important parts of the U.S. wind industry, as discussed above.

U.S. companies face significant challenges in pursuing international markets. Most U.S. renewable energy companies are small entrepreneurial firms with very limited resources. They face aggressive public-private export promotion efforts by foreign competitors that are undercutting them with tied aid, concessionary finance, and other supports to lock them out of these markets. A number of activities are needed to address these opportunities and constraints, including aggressive proactive support of U.S. renewable companies by U.S. export agencies in response to foreign tied aid, concessionary finance, and other supports; trade promotion activities; R&D supports; and a range of technical assistance to foreign countries as they begin to develop their renewable energy resources. The focus here is on R&D and technical assistance.

The DOE Program and Recommendations

The International Program should develop renewable energy and energy-efficient applications, identify where they are or can be the most cost-effective means of providing energy services to people—particularly in developing countries—and then facilitate the development of viable markets around these opportunities through training, technical assistance—particularly to the Multilateral Banks and in-country policy makers—information extension, and other activities.

In addition to the obvious benefits of broadening the base of applications for renewable energy technologies and increasing market penetration, involvement in applications development also provides important feedback to those developing the core technologies.

The existing international program funded through the line item in the renewable energy budget is intended to support Joint Implementation programs, trade missions for U.S. companies, and other activities. The program has minimal resources ($750 thousand in FY1997). Priority activities that should be included as the international program rebuilds are the following:

- **Applications-specific systems integration and development.** Almost all Federal support for renewables has gone into research. To take these technologies the next step towards precommercial systems, **much more attention is needed on applications-specific systems integration and development involving the national laboratories and industry**

- **International collaborative RD&D and joint venture partnerships**. To appropriately focus R&D efforts on viable markets, to encourage developing-country use of renewable energy technologies, and to better position U.S. industry in these rapidly growing markets**, collaborative RD&D and industrial joint ventures are needed.** In-country pilot projects can play an important role in. These projects can spur both U.S. exports and in-country production and economic development.

- **Technical and policy analysis**. **Collaborative RD&D should also include such things as the analysis of opportunities for distributed utility systems, village minigrid development, and regulatory restructuring, as well as the development of analytical tools**

- **Education and training. Ongoing technical and policy training is needed at all levels, such as: energy ministers and their staffs; utility and other executives and decision makers;**

researchers—including extended exchanges between research institutions; and nongovernmental organization staff as key partners for outreach to developing countries; etc.

- **Technical assistance:** To accelerate project development and implementation, **technical assistance to the Multilateral Development Banks is needed to move bankable projects into the pipeline for funding.**

Funding for these international activities within the DOE renewable energy program should be increased to $14 million. This is substantially less than the $27 million that the Administration requested in FY95 for international renewable energy activities, but is an appropriate starting point in building these critically needed activities. Additional funds should be leveraged through joint activities in these areas with the U.S. Agency for International Development (USAID), building upon the President's directives at his United Nations speech in July.

The international program can play a vital role in helping embryonic U.S. renewable energy companies survive, creating export markets, laying the foundation for sustainable energy use in developing countries (thus slowing carbon emissions with U.S. benefits as well), and leveraging economic development in developing countries—particularly rural areas—and thus reducing political instability. U.S. support for these activities within the Kyoto framework would be valuable to the United States, and might also form the basis of a protocol with the developing countries.

For the international program to be effective, trusting relationships with the foreign partner are crucial. Such relationships can only be developed by directly and frankly evaluating the technologies on merit and by demonstrating that the United States is a reliable partner. **To be a reliable partner requires meeting funding commitments consistently and having a stable funding base to operate on over the long term, measured in at least 5 year periods.**

Resource Assessment

Resource assessment determines how much renewable energy (biomass, geothermal, hydro, solar, wind, etc.) is available to renewable energy technologies over large areas and long periods. This information is critical for project developers, providing them with a long-term baseline to help evaluate project viability at particular locations. Without such information, projects cannot go forward, but few developers have the resources or time to develop the analytical tools or the regional multiyear baseline of information necessary.[53] Resource data also assist regional and national energy planning. The role of the resource assessment program is similar in many respects to that of the U.S. Weather Service or the U.S. Geologic Survey.

The resource assessment program examines the various renewable energy resources on an integrated basis, develops geographic information systems to describe and track them, and provides extensive outreach and training to users of this information. It has also developed a number of breakthroughs in computer based and other resource mapping techniques, including solar and some wind mapping from satellite data, and regional wind mapping from topographic models.

The renewable resource assessment line item budget of $2.2 million was zeroed out in FY 1995, because DOE was attempting to respond to general Congressional pressure to eliminate programs and so

[53] OTA (1995).

picked a small program that it could try to keep alive through other means. Core parts of the program have been saved so far—at half the previous budget level—through joint work with other programs, but these critical capabilities are at risk of being lost

The DOE Program and Recommendations

Overall program direction has been good and the range of activities—resource assessment; geographic information system development; information dissemination, outreach, and training; analytical tool development; remote sensing methods; and others—should continue. **Particular attention needs to be given to expanding the assessment activities to provide better coverage and better balance over solar, wind, biomass, hydro, and geothermal resources; identifying appropriate locations for large scale energy storage in support of intermittent renewables, including CAES, and pumped or reconfigured hydro; expanding Geographic Information Systems to include this array of resources; developing improved resource forecasting tools; and improving understanding of microclimates. Special attention should also be given to developing countries, including resource assessments, information outreach, training, and other activities needed in support of U.S. interests there.**

The resource assessment program should be given line item funding at the FY 1995 request level of $5 million, plus $1 million more for international activities, for a total of $6 million.

Analysis

Analysis systematically evaluates technologies, markets, and appropriate public policies. It provides estimates of the costs and benefits of different technologies, their use in integrated systems, and their potential impact on the economic, environmental, and national security challenges that the United States faces. Analysis provides the framework and information to make decisions on what R&D to do; to shape the R&D effort to best fit the evolving energy marketplace; and to understand and help design appropriate public policies and programs for energy technologies and markets—particularly to assist the transition to, and understand the implications of, deregulated and restructured energy markets. Analysis also provides technical evaluations of distributed utility systems, minigrid systems, systems integration, integration of intermittent renewables with the utility grid and with storage—including CAES, hydro, and high-temperature solar thermal, and other technical issues. These are particularly important in considering high penetration levels by intermittent renewables. An important extension of analysis is developing expert tools that enable a broad range of users to conduct their own independent analyses of such issues for their particular applications.

Analysis thus plays a critical role in developing R&D programs, understanding markets, evaluating the impact of public policies, and determining how all these factors interact. It is especially important for RETs as these technologies have different technical characteristics, require different institutional structures and public policies, and address different markets and market mechanisms than do conventional technologies that have well developed markets and infrastructures as well as strong industries to back them.

The analysis program has done much useful work on the above issues. The program focus on technology analysis—distributed utility system, minigrid systems, systems integration and intermittent integration with utility systems—should be strengthened, as should strategic analysis of technology opportunities with regulatory restructuring. Further analysis is also needed of financial issues—including options valuation, portfolio standards, economic impacts, and externalities. One important activity should be to work with the Energy Information Administration (EIA) in better integrating the evolving understanding of the technical and economic prospects for various RETs in EIA energy forecasts, under alternative policy scenarios. For example, it is important to develop improved learning and experience curves for new RETs and use these curves to better understand how RET prices might evolve and how RETs might contribute to national energy needs over time, under alternative variants of a Renewable Portfolio Standard.

Despite its importance, however, analysis has been sharply cut back over the last several years and has had no line item budget for support. About $3 million is being spent on analysis during FY1997 or about 1.2 percent of the total in the Office of Utility Technologies budget. **To ensure core program support, a line item budget for analysis is necessary and should be funded at a level of $6 million.** This support can play an important role in guiding development of these technologies, markets, and public policies and can help ensure best use of taxpayer dollars in meeting our economic, environmental, and security challenges.

CONCLUSION

RETs offer major potential benefits in addressing the multiple challenges posed by the energy system in the 21st century. Remarkable progress that has been made for many RETs over the last decade, and the DOE has made major contributions in making these advances possible. Moreover, there are good prospects for further technical and economic gains for a wide range RETs with further development; most major program goals should be achievable in one or two decades time, with required cumulative program support levels that are modest in relation to potential benefits. In light of these benefits, the recent progress, and the auspicious outlook for further gains, the Panel believes that the DOE should strengthen its R&D program as proposed, in conjunction with complementary demonstration and commercialization programs, with the aim of making RETs widely competitive with conventional energy during the first two decades of the next century.

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