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Renewable Energy: Rapidly Maturing Technology for the 21st Century

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Significant converging trends will enhance the penetration rate of renewable energy in the world market. It is a fact that renewables have moved past the experimental stage and are becoming serious market contenders. The level of maturity of four renewable energy technologies is discussed, and the emerging application of these technologies to rural and remote sites in the form of hybrid systems is presented.

I. Introduction

IT has been 25 years since the oil embargo sent shock waves throughout the Western World, as a rude awakening that a country's energy security, based on imported oil, can vanish overnight. At that time, the U.S. depended on imported oil for 32% of its domestic consumption. Today, the U.S. imports 52% of its oil from foreign producers. Figures 1 and 2 show energy production, import, and export by source in the U.S. from 1949 to 1996.[1]

One of the beneficial outcomes of the oil energy crisis of the early 1970s was a careful look at alternative resources that would reduce U.S. dependence on foreign oil. Renewable energy received serious consideration as one such alternative resource, both in the U.S. and worldwide. Amidst the enthusiasm of attaining energy independence in the shortest possible time, unrealistic goals were set by the Carter Administration in 1977 of 20% renewable energy resources for the U.S. by the year 2000.

Marchetti and Nakicenovic[2] discovered a regular pattern in the substitution of one energy source for another that shows that 23 years was unrealistic. Employing available data on the use of various primary energy forms such as wood, coal, oil, natural gas, and nuclear energy, Marchetti and Nakicenovic found that the penetration of a given energy technology starts with a buildup rate that is exponential, as it grows to 50% of the market it serves. Nevertheless, for global systems, takeover (or 50% penetration of the technology) requires 100 years. For smaller systems, this market penetration is shorter, or 40–50 years (Fig. 3). Based on these observed patterns, the maximum market share for renewable energy in the U.S. by the year 2000 should be closer to 5% (Fig. 4).

In this paper we attempt to show that renewable energy technologies are on target with the Marchetti and Nakicenovic[2] prediction, and that they do present an economically viable alternative to fossil fuels and nuclear power. In Sec. II, we discuss the emerging trends that will boost the use of renewable energy resources. Section III develops a morphology for solar energy conversion modes. Section IV presents the status of four key renewable energy technologies. Finally, in Sec. V, we identify a promising new application of solar/wind technologies for rural and remote site power.

II. Five Converging Trends

Today, 25 years after the 20% goal was set, renewable energy technologies have finally begun to resonate with significant trends that are converging to shape the energy future of this country and the entire world. Alan Hoffman of the U.S. Department of Energy Office (DOE) of Utility Technologies identified the following five trends:

A. World Energy Demand Growth

As the rest of the world tries to catch up economically with the developed countries, energy demand continues to grow at a robust pace. As of the writing of this paper, the world electricity demand rate shows a steady upward trend of 1.5–2.0% per year. Figure 5 illustrates the percent change in electricity output in the decade of the 1990s. A 2% per year population growth in less-developed countries (LDCs), coupled with steady economic growth, resulted in a growth in commercial energy consumption of about 4% per year in LDCs in the past few decades. At this rate, energy use doubles every 17 years. In industrialized countries, energy consumption grows at about 1% per year. As a consequence, if these trends continue, energy consumption in LDCs would surpass that of the industrialized countries around the year 2010.

B. Global Environmental Awareness

By the early 1990s, energy markets were being shaped more by environmental problems and responses, than by economics and politics of oil. Something akin to eco-shock has emerged as a result of the forest death crisis that struck central Europe in 1982, caused mainly by coal-burning powerplants, followed by the explosion at the Chernobyl nuclear powerplant in the Ukraine in 1986, then the 1989 *Exxon Valdez* wreck with its extensive oil slick, the discovery of the ozone hole, and finally, the realization that a significant global warming trend is on the move. In June 1992, 106 heads of state or government gathered in Rio de Janeiro for an Earth Summit to sign a treaty designed to stabilize the Earth's climate, greatly increasing emphasis on renewable energy resources.

C. Energy Security

The collapse of the Soviet Union in 1989, followed by the collapse of the economic and energy infrastructure of its former Republics, has raised serious energy as well as political and economic specters. Security risks associated with the unequal distribution of fossil fuel resources throughout Eastern Europe, the former Soviet Union, and many developing countries, pose major destabilization threats. Renewable energy (wind, solar, biomass, minihydro), on the other hand, is quite equitably distributed with good renewable energy resources of one sort or another available to every country in the world.

D. New Technology Options

Since the energy crisis of the 1970s, the new emphasis placed on alternate energy resources for most of the developed

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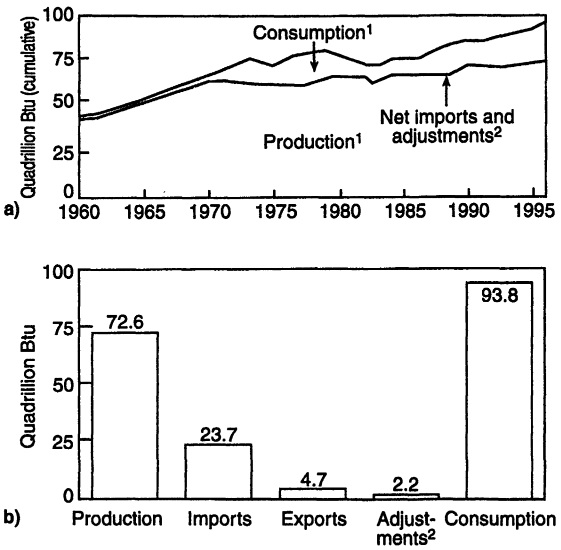


Fig. 1 Energy overview: a) 1960–1996 and b) 1999. [1]There is a discontinuity in this time series between 1989 and 1990 because of the expanded coverage of nonelectric utility use of renewable energy beginning in 1990. [2]Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for-supply.

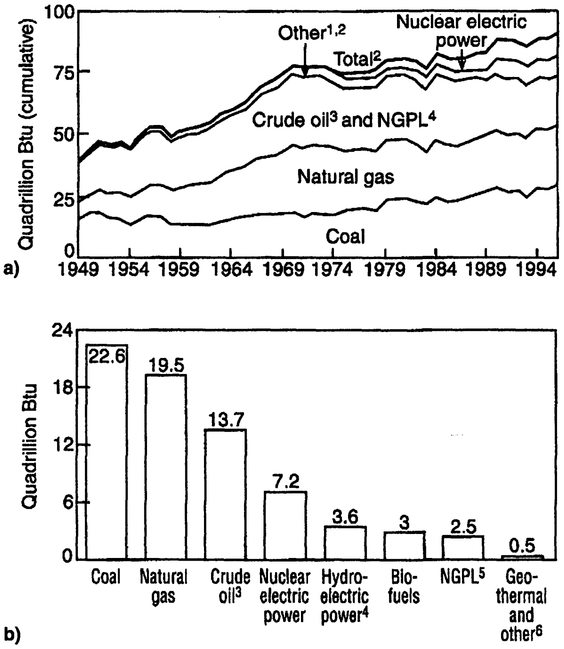


Fig. 2 Energy production by source: a) 1949–1996 and b) 1996. [1]"Other" is renewable energy and pumped-storage hydroelectric power. [2]There is a discontinuity in this time series between 1989 and 1990 because of the expanded coverage of nonelectric utility use of renewable energy beginning in 1990. [3]Includes lease condensate. [4]Conventional and pumped-storage hydroelectric power. [5]Natural gas plant liquids. [6]"Other" is solar and wind energy.

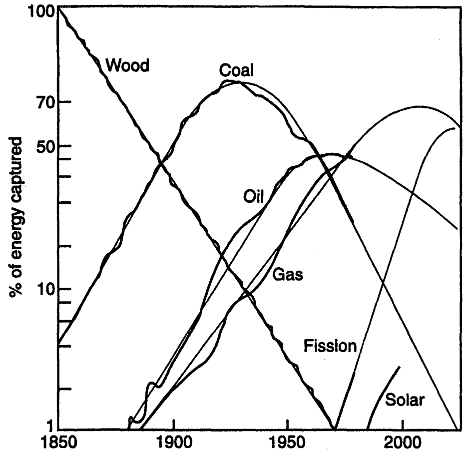


Fig. 3 Market penetration history and projection for the U.S. (Marchetti rule).

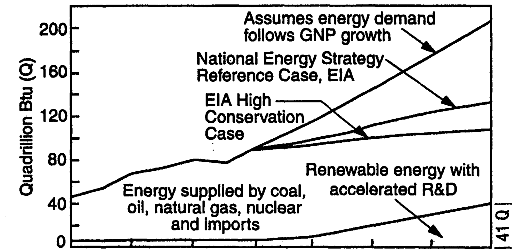


Fig. 4 Contribution of Renewable Energy. Sources: National Energy Reference and High Conservation Cases, EIA; National Energy Strategy Interlaboratory White Paper for Renewable Energy.

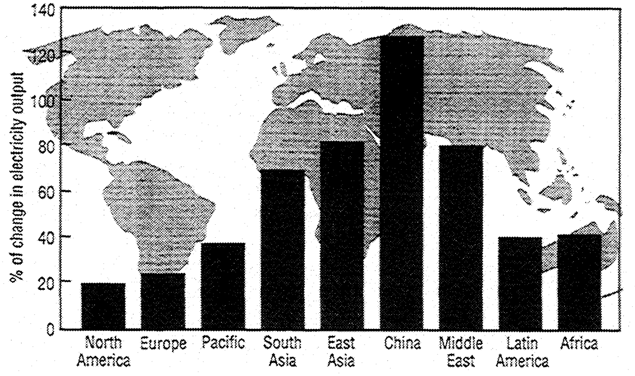


Fig. 5 World Energy Demand 1990–2000. Source: World Energy Outlook, IEA, 1993.

and developing countries, has finally led to the development of economically feasible technologies such as efficient gas turbines, better insulation of buildings, energy-saving devices and appliances, plus several solar-, wind-, and geothermal-based sources of energy utilization that will soon make a measurable impact on the world energy budget.

E. Increasing Business Interest

Generating and distributing electricity is already an $800 billion annual business (twice the world auto industry). The market for human-scale energy systems rather than gigantic projects, has become enormous. There are ~2 billion people in the world today who do not have a light bulb, many of these people cannot be reached by traditional power lines. Add to this the first steps taken by many developed countries, including the U.S., in creating fully competitive wholesale electric markets, and you have the making of potentially lucrative business opportunities in the world's energy sector, including renewables.

The convergence of these trends has given renewable energy technologies a significant boost, as an economically feasible alternative to fossil fuels and nuclear power. In November 1997, seeing the opportunity posed by these trends, the Panel on Federal Energy R&D, President's Committee of Advisors on Science and Technology, Executive Office of the President of the United States, published a 40-page report, recommending the doubling of government funds for renewable energy R&D by the year 2003 ("Federal Energy Research and Development for the Challenges of the Twenty-First Century").

III. Categorizing and Selecting Renewable Energy Alternatives

A. Morphology of Renewable Energy

The commonly accepted grouping of energy resources under renewable energy includes solar, wind, biomass, small hydro, and geothermal energies. However, solar radiation is, in fact, the main source of all renewable energies, except geothermal. To illustrate this, we note that solar energy can be converted into a number of useful end products via a wide spectrum of conversion technologies.[3] A helpful way of categorizing technologies is to develop a morphology of solar conversion systems. Figures 6–8, first developed by Grosskreutz[4] (see also Touryan[3]), illustrate a morphological breakdown of solar conversion modes by generic type. When solar radiation is absorbed by a material, two primary processes ensue: 1) vibrational excitation of atoms and molecules in the absorber produce heat that leads to end products via the thermoconversion path; and 2) selected quantum processes in the absorber, through electronic excitation and charge transfer, lead to useful end products via the photoconversion path. The detailed morphology of these two paths is exhibited in Figs. 7 and 8. The salient features of each process are described next.

1. Thermoconversion Path

There are five primary products associated with the thermoconversion path illustrated in Fig. 7. Of these, hot fluids, with or without concentrators, represent a direct conversion mechanism that is the most commonly known solar conversion technology. The other four are often classified as indirect conversion technologies in that solar radiation first energizes other media, such as the atmosphere (winds) and the oceans, to which man applies a conversion technology to extract useful power. The boundary that separates the cross-hatched area from the open area designates the cutting edge of research and development. To the left of this boundary, the conversion technology is mature and is either in an advanced engineering development stage or is commercially available. Electricity and space heating represent the most familiar end products of thermoconversion. Process heat, fuels and chemicals are more recent entries into the arena of solar thermoconversion applications. Because of its end-use matching flexibility, process heat may have a larger quad impact than electricity. Fuel and chemical production adds a new dimension to energy storage in solar applications, namely, spatial displacement of energy, allowing easy transport of energy from one region to another.

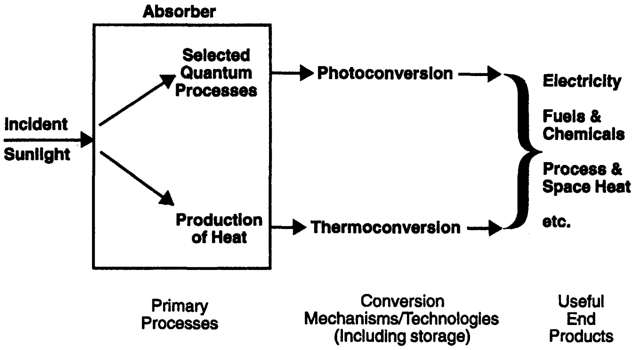


Fig. 6 Solar radiation processes and conversion paths.

2. Photoconversion Path

There are three primary products associated with the photoconversion path illustrated in Fig. 8. The common features to all three products are electronic excitation processes (in contradistinction to vibrational excitation for the thermoconversion path), followed by charge separation, and charge transfer mechanisms that eventually lead to electricity generation or to energy storage for fuel production. In semiconductors (photovoltaics), photon absorption and electronic excitation involve primarily photosensitive atoms, whereas in photosynthesis they involve organic molecules, and in photochemistry they primarily involve inorganic molecules. One should observe here that unlike the taxonomy of the thermoconversion paths, the cross-hatched area covers a much larger percentage of the photoconversion path because of the less mature technologies. The exception, of course, is conversion of biomass created by photosynthesis such as by combustion or fermentation, which is as old as civilization itself and represents indirect photoconversion. Also, the dominant end product of photoconversion is fuels and chemicals. Electricity production is the primary output of photovoltaic conversion, and space heating is the primary output of direct combustion.

B. Criteria for Selecting a Solar Technology

The solar conversion technologies identified in the preceding text are at various stages of technological and economic read-

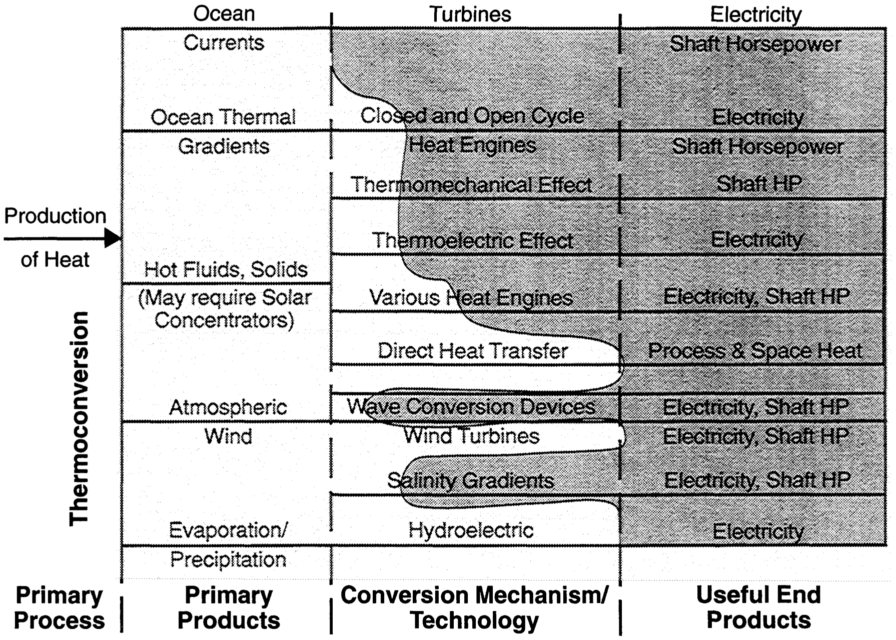


Fig. 7 Detailed morphology for solar thermoconversion paths.

iness. The degree of maturity ranges from available commercially to those that are in a robust embryonic stage, and finally, those that would make no substantial impact on the market until after the year 2010.

Criteria for classifying the various technologies, whether they are ready commercially or not, can be generally grouped in four categories. These categories are useful for prioritizing and selecting the optimum solar conversion technologies for a given application. These four categories are cost, performance, market potential, and possible negative impacts. A detailed breakdown of the categories is shown in Table 1. Most of the specific criteria are self-explanatory and do not require further elaboration; however, a few words of explanation are in order for capital cost, net energy balance, availability, and environmental impact.

The capital cost of renewable energy is by nature relatively high. Because the solar radiation incident upon the Earth's surface is diffuse, all solar technologies require large and often costly collection systems. The initial capital cost of these collection systems is, however, offset by low operating costs, including little or no fuel cost.

Large collection systems also imply material-intensive structures that could require large amounts of energy input before the particular solar technology can provide net energy output. In fact, special care should be exercised in the design and implementation of several solar technologies to ensure a net energy gain from the system over its intended lifetime utilization. This is particularly important when the fuel used to manufacture solar devices, components, and systems is a petroleum product.

Availability of renewable energy reflects the fact that solar energy conversion is strongly site dependent. Certain technologies are therefore better suited to a given geographic area than others. In the U.S., e.g., solar thermal conversion would be ideal in the Southwest; wind in Hawaii and the Midwest; biomass in the Northeast and Northwest; and ocean thermal conversion technology in the Caribbean Islands. The availability criterion can also be used to measure the need for storage and/or hybrid operation with fossil fuel backup, such as diesel generators, both for time and space displacement of those solar energy conversion schemes that depend on an intermittent source, viz., solar heating and cooling, solar thermal power, photovoltaics, and wind.

Regarding environmental issues, wind power has received the most sustained criticism. Although wind turbines do not contribute to net CO_2 or other greenhouse gases to the atmosphere, and produce no pollutants to soil or water, no human activity is without environmental consequences. Possible en-

Table 1 Criteria for selection of optimum solar technologies

Criteria	Dimension or scale
I. Cost	
Capital cost	\$/kWe, \$/GJ/yr, \$/yr
Levelized O&M cost	Mil/kWh, \$/GJ, \$/l, or % capital cost/yr
Return on investment	Payback in years of % invested (against distillate oil)
II. Performance	
Efficiency (first and second law)	Theoretical and actual, %
Availability/capacity factor	Ratio of average load to capacity rating
Reliability/durability	Subjective scale, yr
III. Market potential	
R&D needs	\$ of expenditures (per year or cumulative, including demonstration or engineering)
Application flexibility	Quad (exajoule) impact
IV. Negative impacts	
Environmental impact	Subjective scale (beneficial or adverse)
Operational safety	Subjective scale
Materials availability	Strategic vs nonstrategic
Net energy balance or energy payback period	(Payback period in years, type of fuel needed, boundaries)

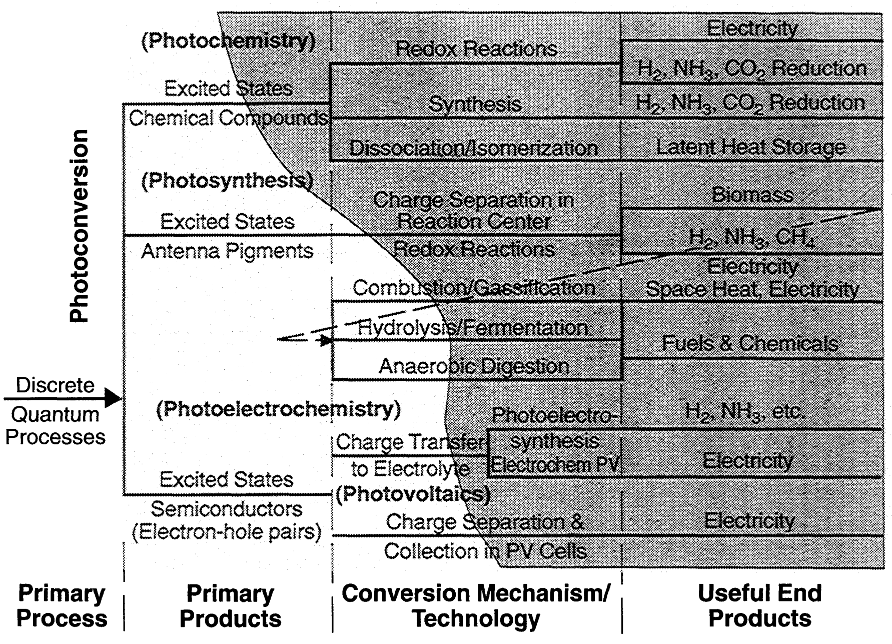


Fig. 8 Detailed morphology for solar photoconversion paths.

vironmental effects of wind-turbine usage can include impacts on birds and animals, noise, television interference, aesthetics, worker safety, and effects on vegetation. After a decade of wind-farm operation in California (1600 MW), the only discernible negative impact on wildlife involves the fatal interaction between birds of prey and wind turbines. Mitigation strategies have been developed (such as the redesign of tower tops), and work is ongoing. The acoustic noise from turbines is both impulsive (thumping) and broadband (swishing). Engineers have reduced aerodynamic noise in recent years by design changes, such as decreasing the thickness of trailing edge of blades and by orienting the blades upwind of the tower. Finally, the use of composite materials and plastics in advanced turbines, minimizes electromagnetic interference.

IV. Status of Four Key Renewable Energy Technologies

It is easy to cite at least seven reasons why the expanded use of renewables makes sense for the world's energy budget in the 21st century. These are proven effectiveness and reliability of advanced wind/solar technologies that are cost competitive in many applications; suitability for rural, off-grid locations; significant economic growth and job creation potential; fuel cost is zero or low with no risk of escalation; renewable energy is environmentally responsible; and, finally, renewable resources enhance energy self-sufficiency. In this section, we will focus on the first three reasons just cited, as to why the use of renewable resources in the 21st century is a realistic option.

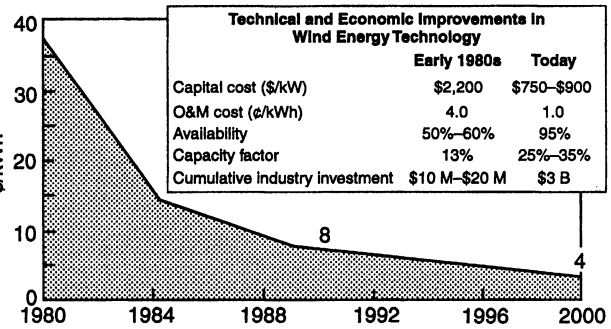
Of the various renewable energy technologies, a number can be considered mature and are now commercially available. Several are already cost-effective, either in the U.S. or abroad. The list includes hot water for domestic consumption, industrial process heat using hot water and steam from parabolic trough concentrators; horizontal and vertical axis wind turbines, either grid connected or in small hybrid operation (see Sec. V); direct combustion of biomass (wood waste, cofired or stand alone); geothermal power (direct steam), and small hydro (less than 10 MW). To this list can be added crystalline silicon and amorphous silicon photovoltaic (PV) panels in remote, off-grid operations, as well as in certain niche markets and ethanol from corn or bagasse, as additives to gasoline (in lieu of methyl tertiary butyl ether). Finally, passive designs for residential and commercial buildings are in increasing use worldwide, where sunshine is abundant. On the other hand, technologies harnessing ocean thermal gradients, ocean waves and currents, or tidal power or salinity gradients, which received much attention in the 1980s, have not proven to be economical and have been de-emphasized. Limited space does not permit us to discuss all of the renewable energy technologies and their market potential in detail. We, therefore, select four key technologies and briefly discuss their present status and market readiness. These are wind power; PV power; solar thermal energy; and ethanol from biomass, where efficiency improvements and cost reductions are occurring at a rapid pace.

A. Wind Energy

Wind energy developers installed more than 1200 MW of generating capacity worldwide in 1996 for the second year in a row, bringing worldwide wind energy capacity to 6200 MWe. In the U.S. alone, wind turbines produce more than 3.5 billion kWh of electricity each year, enough electricity for a city the size of San Francisco. The purchase price of wind-turbine generators has fallen from over $2000 per rated kW in 1984 to between $750 and 900 per rated kW in 1996 (see Fig. 9). O&M (operation and maintenance) costs have fallen from 13.4 cents/kWh to 5 cents/kWh over the same period. Wind powerplants have several characteristics that make them attractive to utilities and their rate payers. These are 1) predictable annual operating costs, because they consume no fuel; 2) modularity, ranging from 100 kW per turbine to 750 kW; and 3) they can help a utility reduce its net emission per kWh.

However, for wind-generated electrical energy to compete with natural gas and coal, the next generation wind turbine designs must reduce costs to 4 cents/kWh or less from current levels of 6–7 cents/kWh now and also improve performance and reliability. The U.S. DOE has made projections for the most likely technology evolution trends for wind turbines.[5,6] Figure 10 shows cost of energy (COE) projections for different wind-speed sites vs time, plotted with calculated COE values for specific turbine designs (shown as discrete data points). The COE values have been computed for sites with a Rayleigh distribution of wind speeds, using constant 1992 dollars, and the financial assumptions specified in the 1993 Annual Energy Outlook.[7] The methodology used to compute COE is a required-revenues approach adapted from the Electric Power Research Institute Technical Assessment Guide. Figure 10 also includes the fuel COE generated using oil, natural gas, and coal technologies, including the variable operation and maintenance costs. Notice that the cost of coal-generated electricity decreases with time, reflecting expected improvements in the technology. This figure shows that wind technology is now competitive with natural gas at the higher 7.2-m/s wind-speed sites; however, to be competitive with advanced coal technology, further improvements will be required during the next decade.

Hock et al.[7] identified four basic approaches to improving the cost effectiveness of wind-turbine designs: increased energy capture, reduced hardware costs, reduced operation and maintenance costs, and improved wind farm design and operation. Well-sited, variable-speed turbine systems on tall towers could provide energy production well in excess of 1200 kWh/m^2, which is nearly double the values obtained for turbines designed in 1984. Three configurations may be compet-



Technical and Economic Improvements in Wind Energy Technology

	Early 1980s	Today
Capital cost ($/kW)	$2,200	$750–$900
O&M cost (¢/kWh)	4.0	1.0
Availability	50%–60%	95%
Capacity factor	13%	25%–35%
Cumulative industry investment	$10 M–$20 M	$3 B

Fig. 9 Cost of electricity from wind.

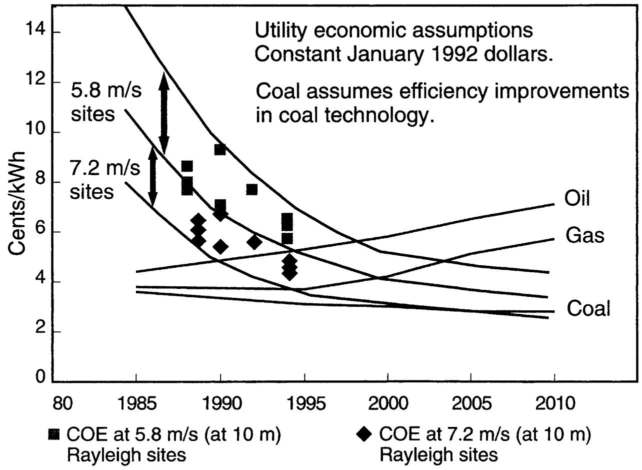


Fig. 10 Cost of energy projections for wind turbines. Source: "Technology Evolution for Wind Energy Technology (draft)," U.S. DOE, June 7, 1993.

ing in the 2000 time frame: advanced three-blade; lightweight teetered, and lightweight vertical axis[8] wind turbines. In general, each of these competing turbine designs will probably incorporate one or more of the following features[7]:

1) Tall towers: strong, lightweight materials and improved load prediction codes should allow turbine designers to increase tower height to 60–70 m to capture stronger winds.

2) Advanced airfoils: field testing of the National Renewable Energy Laboratory and Sandia National Laboratories designed advanced airfoils has shown energy capture improvements as high as 30% over the 1980 airfoils.[9]

3) Lightweight, more flexible: lightweight, flexible turbine designs are more complex to design and require more sophisticated structural dynamics codes, but the weight reduction can potentially reduce costs significantly.[10]

4) Variable-speed operation: several investigators have estimated the potential energy capture improvement from using variable-speed turbines to be 10–15%, which is about the same level as the current added cost for variable-speed power-conversion equipment. However, the decreasing cost of solid-state electronic devices and other load-reduction and power factor control benefits make this a promising option for the future.[11]

5) Low-speed operation: similarly, several investigators have estimated the potential energy capture improvement from going to low-speed turbines to be 10–15%, which is again about the same level as the cost increase. Once again, however, the decreasing cost of solid-state electronic devices and other load-reduction and power factor control benefits make this a promising option for the future.[12]

6) Larger turbines, 500 kW to 1 MW: some turbine designers believe that increasing turbine size will reduce the cost of energy, although there is no consensus for this viewpoint. The experience of the early 1980s in the U.S., and analyses conducted by European manufacturers,[13] counter this argument. Still, site-related land and infrastructure costs, in addition to operation and maintenance costs, could sway the argument in favor of larger rotors. This will remain an open issue until larger turbines are operated in a real utility environment.

7) Other factors: advanced control systems, optimized wind farm layout and operation, and advanced manufacturing approaches will also contribute to increased cost effectiveness.[14]

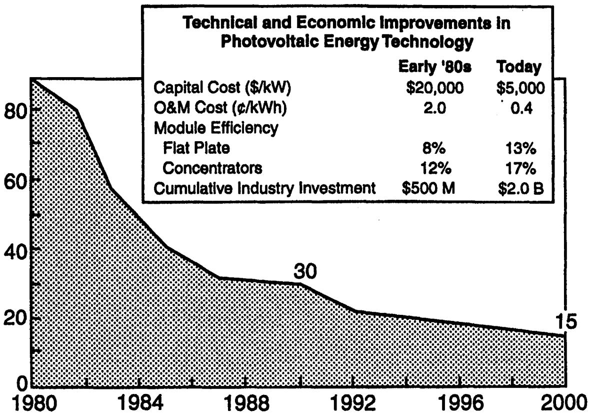
B. Photovoltaic Power

Direct conversion of solar photons to electricity via the PV effect requires no moving parts or intermediate states.[15,16] When economical in location of high solar insolation, PV systems represent the ideal source for electric power generation because they can be applied to every sector of the economy; i.e., consumer/specialists, residential, industrial, rural, and the utility grid. The PV cell technology is being developed along three major thrusts: crystalline silicon; III–V semiconductors; and thin film technologies (polycrystalline and amorphous, with or without concentrators).

1. Economics and Niche Markets

Figures 11 and 12 show the decrease in the cost of electricity from PV and the market evolution from remote applications (today) to bulk power. The manufacturing learning curve illustrated in Fig. 13 shows how PV module prices have dropped as a function of cumulative module shipment. The necessary and sufficient condition for making PV modules competitive is to improve the PV cell efficiency and simultaneously reduce the manufacturing costs of PV panels.

In addition to remote applications, PV systems have been shown to be cost-effective in dozens of applications within the service territories of electric, gas, and communications utilities. Some of the urban applications include: lighting (streetlights, signs, etc.); monitoring; emergency call boxes; irrigation control; and fleet battery charging.[17] In addition, a careful study conducted by a team[18] has identified cost-effective market niches for customer-sited PV in the U.S. today. The analysis was done in two steps: 1) identify and map attributes for the 50 states, including utility electric rates, solar resource, PV capacity factor, tax credits and net metering; and 2) conduct financial cash-flow analysis and market ranking. The financial analysis consisted of new residential development with 1-kW PV systems, with cost made part of the homeowner's mortgage, 10% down, 30-year loan, 8% fixed interest rate, and 3.5% inflation rate.



Technical and Economic Improvements in Photovoltaic Energy Technology

	Early '80s	Today
Capital Cost ($/kW)	$20,000	$5,000
O&M Cost (¢/kWh)	2.0	0.4
Module Efficiency		
Flat Plate	8%	13%
Concentrators	12%	17%
Cumulative Industry Investment	$500 M	$2.0 B

Fig. 11 Cost of electricity from PV.

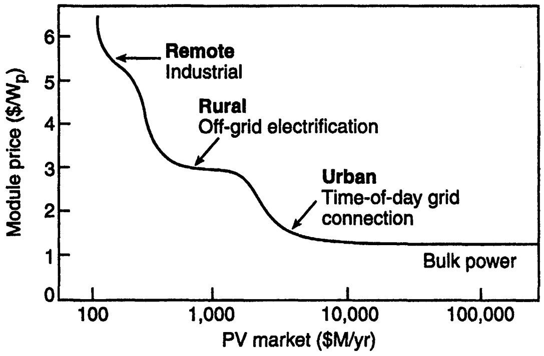


Fig. 12 PV market evolution.

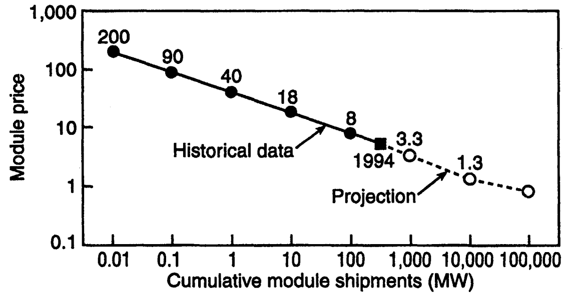


Fig. 13 PV manufacturing learning curve $/W (1994 $).

Figure 14 shows three market tiers: top five, emerging, and states where significant incentives are needed. The top five, Hawaii, California, Arizona, New York, and Massachusetts, emerge as cost-effective today. It is important to note that many applications such as air conditioning that require energy and drive a utility's load are synchronized with the intensity of the solar resource, and PV can provide load matching with the load requirements of a utility. Areas of high effective load-carrying capacity with PV have certain characteristics such as intense summer heat waves, high daytime commercial demand, and low heating demand.

2. Status of Cell and Module Technologies

A comprehensive (542 references) review of the PV cell and module technologies has been written by Kazmerski.[19] Because

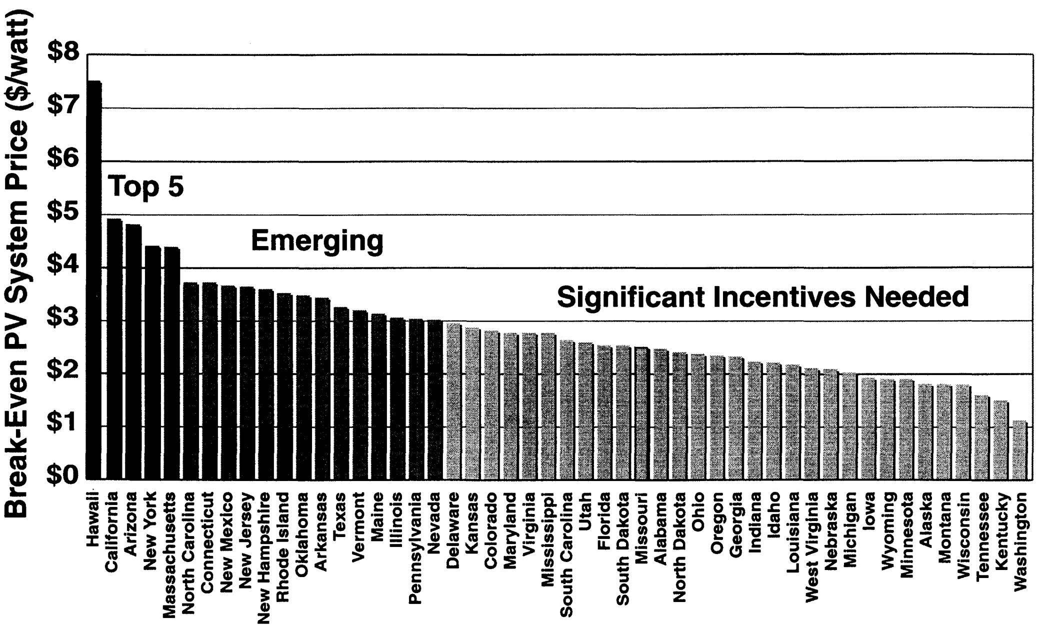


Fig. 14 State-by-state ranking: 3 Market tiers.

of limited space, we present highlights of the three generic types of PV cell/module developments, covered by Kazmerski, in his review.

Single-crystal and polycrystalline silicon (Si). Silicon has been, and continues to be, the foundation of the PV industry. The material is abundant, comprising about 20% of the Earth's crust. Because of its importance to the electronic markets, more is known about the electrical, optical, chemical, and physical properties of this semiconductor than any other material. Silicon solar cells have demonstrated reliability for both space and terrestrial environments.[20] Examination of its fundamental characteristics, i.e., lower than ideal bandgap for terrestrial use, indirect-bandgap type with lower absorption coefficients, might have redirected interest in Si for PV from a theoretical viewpoint. However, these cells have provided some of the highest single-junction efficiencies and short-circuit densities among PV material options. The major limitation to Si, rather than performance, has been the cost of purifying the silicon and growing crystals with it. Much of the industry and research activity in this technology has been guided toward 1) lowering the materials and cell-processing costs (including specific attention to alternative Si source materials and improving the manufacturing yields, handling, and steps); and 2) improving the operational performance of the device to near theoretically predicted values.

Today, large area laboratory cells exceeding 23% have been confirmed for single-crystal Si cells, and 20% module efficiencies. The corresponding efficiencies for polycrystalline cells have been 19 and 17%, respectively. With these efficiencies, the energy payback time for crystalline Si PV modules vary from 2.6 years for the sunbelt region, to 5 years in continental climate, high-altitude regions. In 1996, worldwide production shipments were about 90 MW of PV cells, about 80% of this being crystalline Si. (One should note that this capacity is nowhere near sufficient to meet the gigawatts per year demands forecast a decade from now.)

3. *III–V Semiconductors*

Semiconductors such as GaAs, GaAlAs, GaInAsP, InAs, InSb, and InP have long received attention for photovoltaic applications, because they have exceptional, near-optimal, and alterable characteristics.[21] Strong support for III–V photovoltaics is tempered by equally strong expressions of doubt about their terrestrial validity. Knowledge about the properties of these materials has been enhanced because of their use in high-speed and optical electronics. Cost is the usual factor cited for limiting widespread use of III–V solar cells in terrestrial PV. Space markets have expanded as they are less sensitive to cost, but more sensitive to performance and radiation resistance.[22] Under one-sun operation, efficiencies as high as 25% for large cells have been recorded. Under multiple sun operation (with concentrators) or when used in tandem, as multiple junction cells, efficiencies have exceeded 30%. In tandem cells, two or more cells are stacked in such a way that the portion of light not absorbed passes through the top cell and is absorbed by the bottom device, thus circumventing the 30% constraint for a single cell, imposed by the second law of thermodynamics. For space applications, where payload weight is a premium, tandem cells, although more expensive than single junction cells, can easily offset the extra cost through their increased efficiency.

4. *Thin Film Devices*

The arguments for thin-film devices for terrestrial PV are primarily based on materials utilization (less required and more efficient module-area coverage), large-scale manufacturing potential, and better energy economy for production.[23,24] Additionally, cost and performance advantages can be realized by using, other than Si, semiconductors in such thin layers. The two serious contenders for polycrystalline thin films are the copper–ternary, copper–indium–gallium–diselenide (CIGS) cells and cadmium–telluride cells. Record efficiencies of 17.7% have been recorded on 1-cm^2 surfaces for CIGS cells and 15.8% for CdTe cells. The major issue for CIGS technology is the implementation of large-scale manufacturing techniques with adequate yields.

One of the most promising thin film cells has been amorphous silicon Si:H cells.[25] As Kazmerski[19] describes it, when first introduced, a-Si:H seemed to be the ideal photovoltaic candidate. Its native bandgap of $\sim$1.7eV could be varied over tenths of eVs by changing the hydrogen content and established the physics of this semiconductor to be different than that of crystalline Si. Its absorption characteristics validated the material's economy with only 1/100 of the thickness needed to absorb the same amount of sunlight as its single-crystal relative. This thin film could be deposited on inexpensive substrates in any dimension for large-scale production. It had spinoffs to other electronic technologies (transistors, flat-panel displays, detectors) that enhanced its scientific interest, investigation, and development. For PV, however, it has one concern, that of instabilities observed when exposed to light (the Staebler–Wronski effect[26]; a concern that has slowed a more rapid deployment as a power-generating technology. However, innovative approaches, using double- and triple-junction a-Si:H cells, have improved the stable operation of a-Si cells, with module efficiencies in excess of 13%.

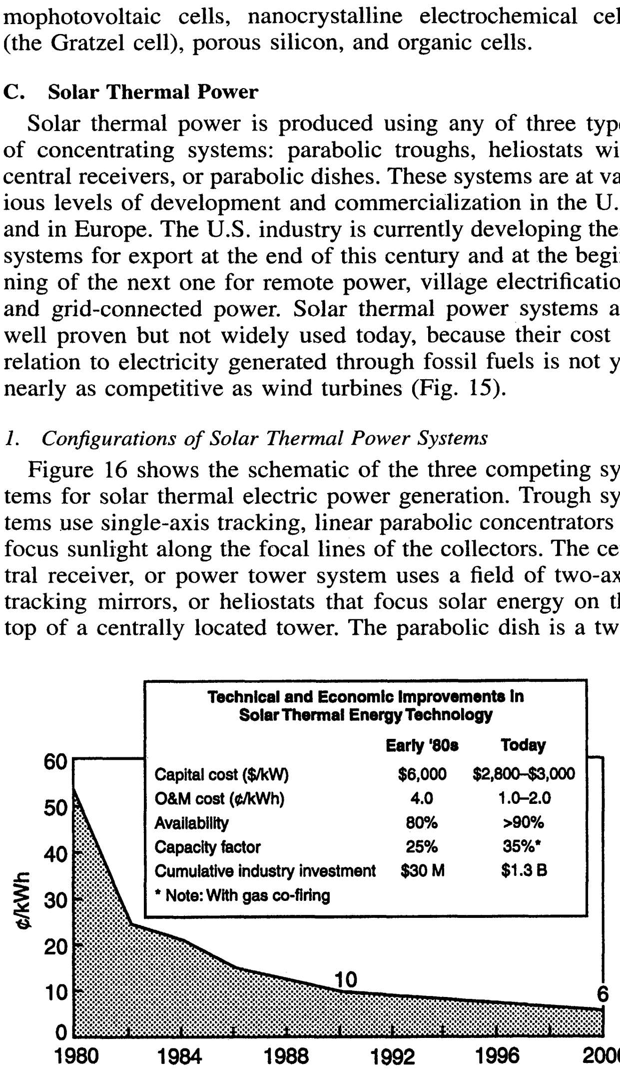
Finally, extensive R&D and manufacturing efforts are underway in all three technologies, using matching funds between government and industry, with the target of $1 per peak watt for PV cells, within the next decade. In addition, basic research continues in other innovative PV devices such as thermophotovoltaic cells, nanocrystalline electrochemical cells (the Gratzel cell), porous silicon, and organic cells.

C. Solar Thermal Power

Solar thermal power is produced using any of three types of concentrating systems: parabolic troughs, heliostats with central receivers, or parabolic dishes. These systems are at various levels of development and commercialization in the U.S. and in Europe. The U.S. industry is currently developing these systems for export at the end of this century and at the beginning of the next one for remote power, village electrification, and grid-connected power. Solar thermal power systems are well proven but not widely used today, because their cost in relation to electricity generated through fossil fuels is not yet nearly as competitive as wind turbines (Fig. 15).

1. Configurations of Solar Thermal Power Systems

Figure 16 shows the schematic of the three competing systems for solar thermal electric power generation. Trough systems use single-axis tracking, linear parabolic concentrators to focus sunlight along the focal lines of the collectors. The central receiver, or power tower system uses a field of two-axis tracking mirrors, or heliostats that focus solar energy on the top of a centrally located tower. The parabolic dish is a two-axis tracking system that focuses solar energy onto a heat engine/generator located at the focus of the dish.

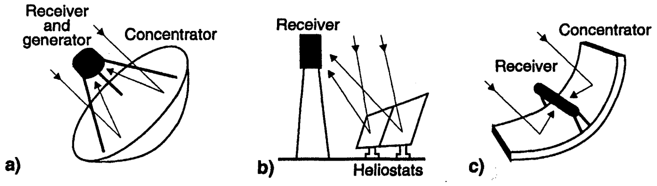


Technical and Economic Improvements in Solar Thermal Energy Technology

	Early '80s	Today
Capital cost ($/kW)	$6,000	$2,800–$3,000
O&M cost (¢/kWh)	4.0	1.0–2.0
Availability	80%	>90%
Capacity factor	25%	35%*
Cumulative industry investment	$30 M	$1.3 B

* Note: With gas co-firing

Fig. 15 Cost of electricity from solar thermal (parabolic trough).



System	Solar Concentration	Operating Temperature	Annual Efficiency
Trough Electric	~ 75 suns	400°C	8 – 12%
Power Tower	~ 800 suns	560°C	12 – 18%
Dish Engine	~3000 suns	800°C	18 – 23%

Fig. 16 Schematic drawing of trough, central receiver, and dish systems.

A comprehensive review of solar thermal power using the above three configurations has been given by Mancini et al.[27] A brief summary follows in this section.

2. Trough Systems

Of the three concentrating configurations, the troughs yield the lowest temperatures and are commercially available for providing industrial process heat. As electric generating plants, the only trough systems in the world currently operate in the Mojave Desert of Southern California, where they deliver 354 MWe of peaking power to the Southern California Edison Company's power grid. These nine trough Solar Electric Generating Systems (SEGS) were installed between 1985 and 1991, and comprise over 90% of the grid-connected solar electricity generated in the world today. In this system, a heat transfer oil is heated in the receiver tubes, which are located at the focus of the solar collectors. The hot oil is then pumped through the steam generator and solar super heater to produce steam for the turbine generator. To deliver electricity at competitive prices with fossil fuel, trough plants will have to deliver electricity at a lower cost than the existing SEGS plants, and will most probably operate in hybrid mode using coal-fired Rankine cycle and natural gas-fired combined cycle systems, reducing both the capital and O&M costs by 50% (from 15 to 7 ¢/kWh).

3. Central Receiver Electric System

Power towers must be large to be economical; they require about one square mile of land to produce 50 MWe of power.[28] Power tower plants are not modular and cannot be built in the smaller sizes of dish/Stirling or trough electric plants and be economically competitive, but they do use a conventional power block and can easily dispatch power on demand when storage is available. In the U.S., the Southwest is ideal for power towers because of its abundant, relatively low-cost land, and high levels of insolation. Similar locations in north Africa, Mexico, South America, the Middle East, and India are also well-suited for power towers.

Solar One, which operated from 1982 to 1988, was the world's largest central receiver powerplant. It proved that central-receiver technology is effective, reliable, and practical for utility-scale power generation. In this plant, water was converted to steam in the receiver and used directly to power a conventional Rankine-cycle steam turbine. The heliostat field consisted of 1818 heliostats of 39.3 m^2 reflective area each. The Solar One project was a joint undertaking of the U.S. DOE and Associates, consisting of Southern California Edison Company, Los Angeles Department of Water and Power, and the California Energy Commission. The project met most of its technical objectives: to demonstrate the feasibility of generating power with a central receiver, 10 MWe for 8 h/day at summer solstice and 4 h/day near winter solstice. During its final year of operation, Solar One's availability was 96% during hours of sunshine.

Based on the experience gained with Solar One, a second system, Solar Two was designed and put into operation in 1997, using molten nitrate salt as the working fluid. Molten salt is liquid at atmospheric pressure, provides low-cost energy storage medium, and its operating temperatures are compatible with steam turbines. To encourage the development of molten-salt, power towers, a consortium of utilities led by Southern California Edison joined with the U.S. DOE to redesign the Solar One plant with a molten-salt heat transfer system.[29] The goals of the redesigned plant, called Solar Two, are to validate nitrate salt technology, to reduce the technical and economic risk of power towers, and to stimulate the commercialization of central-receiver technology. Solar Two will produce 10 MWe of electricity with enough thermal storage to operate the turbine at full capacity for 3 h after the sun has set. As with the trough systems, the solar fossil hybrid option would most likely be the most promising alternative for near-term system or overseas markets. One option would be the combined-cycle power tower, where solar heat is used to heat the turbine combustion air.

4. *Dish/Stirling Systems*

Dish/engine systems operate by tracking the sun and focusing solar energy into a cavity receiver, where it is absorbed and transferred to a heat engine/generator. Although Brayton and organic-Rankine-cycle engines have been used with dishes, Stirling engines (kinematic and free-piston) are used for all of the commercial dish/engine systems under development today. Stirling engines are preferred for these systems because of their high efficiencies (thermal-to-mechanical efficiencies in excess of 40% have been reported), high-power density (50 kW/l for solar engines), and potential for long-term, low-maintenance operation. Dish/Stirling systems are modular, i.e., each system is a self-contained power generator and they hold the record for solar-to-electric conversion efficiency at 29.4% modularity. This is an advantage because these systems can be assembled into plants ranging in size from a few kilowatts to tens of megawatts. An important milestone in the evolution of Dish/Stirling systems has been the use of heat-pipe receivers. The isothermal nature of heat pipes makes possible efficiency, and lifetime gains work more than the incremental cost. The near-term markets identified by the developers of these systems include remote power, water pumping, grid-connected power in developing countries, and end-of-line power conditioning in the U.S.

Cummins Power Generation (CPG) has developed a 7-kWe dish/Stirling system using 24 5-ft-diam stretched membrane, polymer mirror facets. Schlaich Bergermann and partner of Stuttgart, Germany, has developed a 9-kWe dish/Stirling system with a 7.5 m diameter stretched membrane concentrator. Both systems are commercially available. A larger 25-kWe system built by CPG when mass produced, is projected to cost between 6 and 11 cents/kWh.

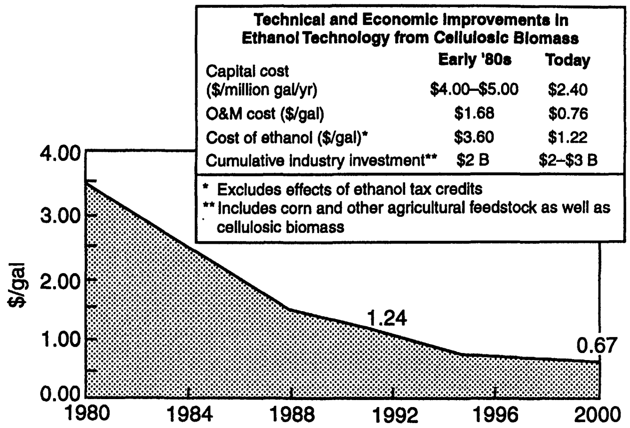
D. Biomass Liquid Fuel for Transportation

Biomass is renewable organic material that consists of 1) terrestrial or aquatic vegetation and 2) animal, agricultural, and forest residues. Of all solar technologies, biomass systems can provide the most direct and efficient replacement for imported oil and gas. Biomass can be collected and burned directly, or as cofeed with coal or gas, for generating steam and electric power using a Rankine cycle. Such systems are commercially available in sizes ranging from 100 kW to 75 MW. Biomass can also be converted to gaseous fuels, liquid fuels, or energy-intensive petrochemical feedstocks. Because biomass is part of nature's CO_2 cycle, the net CO_2 emission from utilizing biomass as a fuel source, will be less than 16% compared with natural gas.

In this paper, we will only address the technology advances of converting biomass feedstocks (waste material or energy crops) to ethanol. Ethanol is an important industrial chemical made through the fermentation of glucose derived from corn or sugar cane. For ethanol to become a widespread alternative transportation fuel, it must be produced from more economical feedstocks than corn or sugar (see Fig. 16). Cellulosic material, such as paper, grasses, forestry or agricultural residues and municipal wastes appear to be such feedstocks.

Unfortunately, these feedstocks contain a large portion of pentose sugars that are largely unfermentable by the current mainstay of industrial ethanol production, the yeast Saccharomyces cerevisae. The rapid and efficient utilization of the pentose sugars in cellulosic feedstocks is an absolute requirement for a commercial biomass-to-ethanol process. Rigorous efforts are ongoing to address this issue.

The introduction of genetic and metabolic engineering to strain improvement in the ethanol industry has lead to the development of a variety of new, significant microorganisms. Enhanced ethanol-fermenting bacteria, such as Zymomomas Mobilis,[30] as well as yeast species with expanded substrate range offers an opportunity for use of lower cost feedstocks and higher profitability. Concerns about performance consistency and robustness as compared with the standard Saccharomyces strains must be overcome before the introduction of these strains will become commonplace.



Technical and Economic Improvements in Ethanol Technology from Cellulosic Biomass

	Early '80s	Today
Capital cost ($/million gal/yr)	$4.00–$5.00	$2.40
O&M cost ($/gal)	$1.68	$0.76
Cost of ethanol ($/gal)*	$3.60	$1.22
Cumulative industry investment**	$2 B	$2–$3 B

* Excludes effects of ethanol tax credits
** Includes corn and other agricultural feedstock as well as cellulosic biomass

Fig. 17 Cost of ethanol fuel from biomass (cellulosic biomass only).

It is instructive to note that when cellulose fermentation becomes commercially viable over the next decade, one can use acres from cropland currently idled by government programs; land for which new crops will be needed. At the current average productivity rate of 6 tons/acre/year (15 metric tons/hectare/year), and using the cropland projected to be idle, in the year 2030, enough biomass could be produced to provide more than 50% of U.S. gasoline consumption per year. If the program goal of 10 tons/acre/year (25 metric tons/hectare/year) is attained, ~80% gasoline displacement could be realized.[31,32]

The critical issues here, of course, are institutional barriers erected by the gas and oil lobby. Unless oil companies themselves buy into ethanol production and utilization on a large scale, extensive use of ethanol for transportation will be an uphill battle even with the projected wholesale price of ethanol from cellulosic biomass reaching 60 cents/gal before the year 2005 (Fig. 17).

In all of the cases just discussed, it is evident that renewable technologies have begun to play an increasingly important role in the world's energy budget. As further proof of the increased rate of penetration of renewable technologies, we now turn our attention to a new promising application for renewable energy technologies in the world market that could easily become the venue that will make renewable energy a significant part of the world energy budget.

V. Renewables for Sustainable Rural/Remote Site Power

It is estimated that two billion people live without electricity and its services worldwide. In addition, there is a sizeable number of rural villages that have limited electrical service, with either part-day operation by diesel generator or partial electrification. For many villages connected to the grid, power is often sporadically available and of poor quality. The U.S. National Renewable Energy Laboratory (NREL) in Golden, Colorado, has initiated a program that involves hybrid systems, to address these potential electricity opportunities in rural villages through the application of renewable energy technologies.[33] The objective of this program is to develop and implement applications that demonstrate the technical performance, economic competitiveness, operational viability, and environmental benefits of renewable rural electric solutions, compared with the conventional options of line extension and isolated diesel minigrids. Hybrid systems are multidisciplinary, multitechnology, multiapplication programs, composed of six activities, including village applications development, computer model development, systems analysis, pilot project development, technical assistance, and Internet-based village power project database. While the current program emphasizes wind, PV, and their hybrids with a diesel generator, microhydro and microbiomass technologies may be integrated in the future. Thirteen countries are actively engaged in hybrid systems for rural and remote applications, and another dozen countries have requested assistance in exploring wind/PV hybrid systems within their territories. Presently, rural/remote site application of renewable technologies is the fastest growing aspect of renewable energy worldwide.

A. Hybrid System and Practical Applications

The main objective of the applications development activities using hybrid systems is to investigate renewable energy-based systems that will reduce the life-cycle cost and/or improve the performance of commercial renewable energy systems, thereby expanding the market for renewables. Many of these applications have the potential to facilitate economic development within the village; a major goal of many international development organizations and host-country national and provincial governments. Electrification of rural villages has the potential to initiate substantial development activities, if electric power were available during daytime hours, and appropriate training and marketing infrastructure were available to villages. However, in most smaller villages served by diesel generators, it is cost-prohibitive to provide daytime power, and therefore, the economic development potential of these villages cannot be realized. Renewable energy systems are better suited to deliver 24-h power in small villages (less than 2000 inhabitants), where income generation and economic developments are being pursued as policy goals.

Hybrid systems are being considered for ice-making, water desalination, water purification, battery-charging stations, and village hybrid power generation. Because many villages have either diesels dedicated to a particular use or a diesel minigrid, they face both economic (fuel cost) and maintenance problems associated with remote diesel operations. Yet in many of these villages, the solar and/or wind resources are good enough to compete economically with the life-cycle cost of diesel operation.

B. System Design

Hybrid systems can be powered by any combination of wind, PV, diesel, and batteries. This level of flexibility has obvious advantages for customizing a system for particular sites resources, costs, and load requirements. The flexibility, however, makes the design process more difficult. It is essential, therefore, to develop design models that can address 1) optimization of a hybrid configuration, 2) the technical and economic performance of hybrids, and 3) the economics of alternative village electricity options. Two such models have been developed. One is called Homer,[34] and the other Hybrid-2.[35] Both are being validated with operational data from the field, and are being used to design systems in rural settings, worldwide.

Briefly, Homer is an optimization model that takes into consideration hourly and seasonal variations in the village loads and resources, simple performance characterizations of each component, equipment costs, reliability requirements, and other site-specific information. Homer identifies the optimal configuration as well as its sensitivity to user specified ranges of input parameters, for screening purposes. In addition to the configuration, Homer outputs include hourly energy flows through each component, the impact of several simple load management strategies, and economic information such as the cost of energy and net present costs of the system. Figure 18 illustrates such a screening analysis for a given wind site. Hybrid-2, on the other hand, is a software that employs a time-series/probabilistic model that uses time-series resource and load information, combined with statistical analysis, and manufacturers' data for hybrid system equipment to accurately predict the performance and cost of hybrid power systems. Hybrid-2 allows for the direct comparison of many different renewable and nonrenewable power system designs.

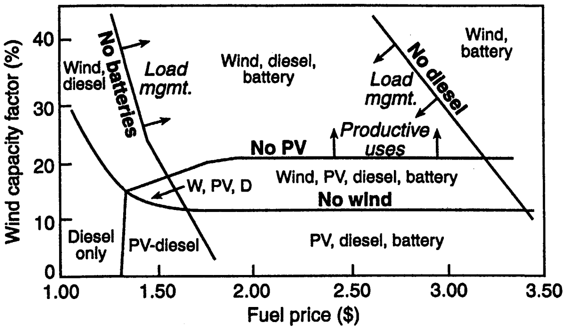


Fig. 18 Typical wind/diesel/battery configuration analysis using HOMER code.

Both Homer and Hybrid-2 require resource data as one of their key inputs. Most potential sites lack sufficient information on solar insolation and/or wind speed, frequency and direction. Automated wind and solar insolation mapping techniques are now available that use the Geographic Information Systems (GIS) software. For wind, e.g., this provides topographical data that are used as inputs for a computerized mapping technique. A variety of meteorological and other geographical data sets are used to support wind mapping projects. This computer mapping system[36] uses an analytical approach and is designed to portray the distribution of the wind resources over a large area. These maps are then used to identify and target areas for possible sites and more detailed wind measurement projects. Space will not permit us to elaborate these design tools further, but a pilot project underway in Alaska, will illustrate the power of these tools.

C. Case Study

Alaska has approximately 250 rural villages that have no link to the central power grids serving the main urban areas. The majority of these villages are served by diesel-driven generators. Because of the extreme remoteness of most of the rural villages, and the lack of roads, the delivered cost of diesel fuel is high, ranging from \$0.80 to 3.00/gallon. The high operation and maintenance costs of diesel generating stations result in electric generation costs that range from \$0.15 to 1.00/kWh. There are also significant environmental hazards associated with diesel power generation, including fuel spills during transport, leaky bulk fuel tanks in the villages, and CO_2 and other emissions.

To reduce the cost of rural power generation and the environmental impact of diesel fuel usage, the Alaska Department of Community and Regional Affairs Division of Energy (DCRA/DOE), in collaboration with Kotzebue Electric Association (a rural Alaskan electric utility) and the NREL, is developing wind–diesel hybrid power technology to be implemented in a pilot project in the village of Wales, Alaska, a native village of 160 people in northwest Alaska. The project integrates three 65-kW wind turbines into the existing Wales diesel power system (75 kW average load). The system incorporates reactive power and dump load control to provide regulation of line voltage and frequency, enabling the diesel gensets to be shut down during periods of high wind. The system also incorporates short-term energy storage to prevent unnecessary diesel starts and maximize fuel savings.

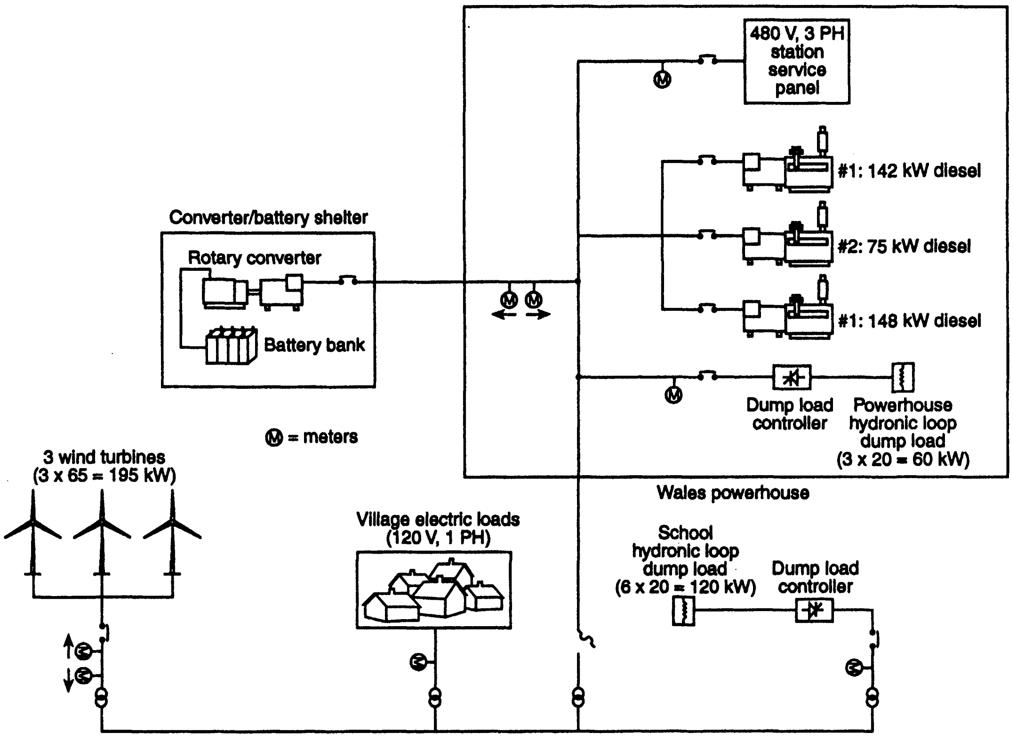


Fig. 19 High penetration wind-diesel system (Wales, Alaska).

Figure 19 gives the schematic layout of the Wales wind–diesel system† (also see Ref. 37). A few important facts should be noted. A high penetration wind–diesel system requires controls, and one of the first steps in system installation is to retrofit all diesels with controls, making them capable of automatic starting, stopping, synchronization, and load sharing. Energy storage using a battery bank is necessary to meet the average load for the system for about 10 min. This will avoid excessive wear and tear on diesels whenever there is a transient wind power drop that could cause the load to exceed the available wind power. Figure 20 illustrates the fuel savings potential and the reduction in cost of energy, as a function of average wind speed for the preceding configuration (levelized over 30 years). The market potential for small hybrid systems is in the tens of thousands, worldwide. Wind electric and PV generators, and their balance of systems, are very different from conventional generation equipment in many aspects, and therefore, somewhat intimidating to the regional rural electricity provider. To make the transition to the comfort level of the village, the systems will need to perform as well as or better than the conventional solutions. Robustness, reliability, quality of service, and serviceability are the technical parameters that the local provider will be interested in evaluating. The performance data, including system, resource and load data, need to be collected, collaboratively analyzed, and reported to the project sponsors.

While the technical viability must be demonstrated, and economic comparisons should be made in the country context, the most significant value of the pilot projects is the development of the institutional viability. There have been countless renewable energy-based, donor-aided rural projects that made technical and (long-term) economic sense, but never were replicated, and in many cases became nonoperational because care was not taken in the institutional aspects of the project.[38] Renewable energy systems, like all energy systems, require administration, operational, and maintenance attention/discipline. The type of institution that will serve the rural electricity needs will depend on the local situation and the regional and national regulatory and legal structure.

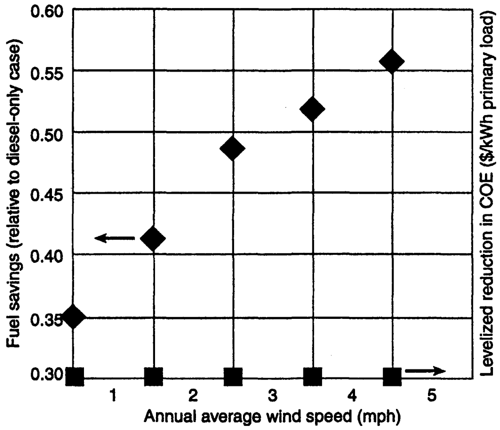


Fig. 20 Fuel savings and levelized reduction in COE vs annual average wind speed [three wind turbines, fuel cost = \$0.48/l (\$1.82/gal), storage size = 33.5 min at average load].

VI. Concluding Remarks

In 1982, when the author published a similar article on the state-of-the-art of solar energy in the *Journal of Energy*,[3] not one solar technology was cost-effective without some type of federal or state tax incentive. The emphasis on commercialization of solar technologies then was market push. Few had noticed the Marchetti rule for market penetration, or market pull for any new energy source. Renewable energy technologies then were immature, detailed resource definition for local conditions were lacking, and significant infrastructure and incentives instituted over many decades favored conventional fuels.

Much has changed since then. The five trends mentioned in Sec. II, namely, growth in world energy demand, a global environmental awareness, a new appreciation for the need of energy security, more mature renewable energy technologies described in Sec. IV, and new business opportunities, are con-

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†Drouillet, S., and Shirazi, M., "Performance and Economic Analysis of the Addition of Wind Power in the Diesel Electric Plant at Wales, Alaska," NREL unpublished report.

verging to give renewable technologies a new boost in the energy market. Rural and remote applications using hybrid systems described in Sec. V, have opened vast new markets, where renewable technologies could make a significant impact. Finally, the opening of the power generation market to competition has led independent power producers to favor smaller, more innovative power projects where renewable technologies do better than most conventional fuels. Although the wind and solar energy industry is still fragile, one will not be too far off the target, therefore by claiming that renewable energy sources could be responsible for 20% of the world's energy budget in 2020.

Acknowledgment

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