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# SOLAR POWER

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*This paper describes categories of solar technologies and identifies those that are economic. It compares the private costs of power from solar, wind, nuclear, coal, oil, and gas generators. In the southern United States, the private costs of building and generating electricity from new solar and wind power plants are less than the private cost of electricity from a new nuclear power plant. Solar power is more valuable than nuclear power since all solar power is available during peak and mid-peak periods. Half of the power from nuclear generators is off-peak power and therefore is less valuable. Reliability is important in determining the value of wind and nuclear power. Damage from air pollution, when factored into the cost of power from fossil fuels, alters the cost comparison in favor of solar and wind power. Some policies are more effective at encouraging alternative energy technologies that pollute less and improve national security.*

## I. INTRODUCTION

Conventional fossil fuels have environmental costs. Petroleum and nuclear power pose national security risks. Solar energy systems appear to be a promising alternative. The raw material is abundant. Average annual solar insolation for the continental United States is about 700 times the total amount of energy used by the nation in a year (Hubbard, 1989, note 37). Solar systems, once installed, are relatively insensitive to fuel cost escalations and supply disruptions. Solar technology does not contribute to the proliferation of nuclear weapons. Solar power plants are not attractive targets for terrorists, nor are they producers of nuclear material that could be diverted by terrorists.

So, then, what are the prospects and problems for solar technologies? Section II identifies major categories of solar options, only a subset of which appears viable in the near future. Section III provides a range of cost estimates for the emerging technologies and compares these costs with current energy options. Because "cost" and "price" need not be the same, section IV highlights some factors likely to affect solar energy usage and the implications for various solar energy development policies.

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## II. AN OVERVIEW OF SOLAR TECHNOLOGIES

In the energy literature, a wide variety of conversion processes have been called solar energy systems. This paper emphasizes active, direct solar energy options with apparent near-term potential in utility-related applications.

### A. *Active and Passive Solar Energy Systems*

Passive energy systems are designed to mitigate the impacts of seasonal temperature extremes and augment natural ventilation processes. Examples of passive solar techniques include window placement, installation of shutters and awnings, and landscaping to control the influx of solar radiation. Active systems use mechanical components to provide energy or climate control. Such systems may be integrated into a building, but some components are distinct from the building itself.

Passive solar energy options conserve significant energy. Energy conservation is not a perfect substitute for energy generation: The opportunity costs of no energy use are extremely high. Active systems, including non-solar as well as solar options, must meet remaining energy needs.

### B. *Direct and Indirect Solar Technologies*

Direct technologies use incoming solar insolation to produce heat or electricity. Solar thermal and photovoltaic systems are examples of direct technologies. Indirect solar technologies are less closely linked to solar insolation. Bioconversion processes, photosynthetic production of organic materials, and hydrogen are examples of indirect solar technologies. Many of these options use renewable energy resources, but this paper does not focus on systems that make indirect use of solar insolation.

### C. *Key Components*

A solar energy system may include collectors, conversion systems, transport facilities, and storage devices. The wide variety of possible designs for each component accounts for the large number of potential systems. All active solar energy systems include a collector, but the other three components may or may not be present. One may classify collectors according to their insolation-utilizing (flat-plate, tubular, concentrating) and sun-tracking (fixed, one-axis tracking, two-axis tracking) abilities. The most common solar energy systems on buildings use fixed, flat-plate collectors. However, fixed flat-plate collectors are subject to shading and other forms of insolation reduction and have a relatively low conversion efficiency (energy output per surface area of unit collector). Several more sophisticated collector designs have been developed to offset these difficulties. For example, the solar thermal systems operated by Luz International Limited, Los Angeles use parabolic reflectors to concentrate solar insolation (Johnson, 1990; Luz, 1989, 1990).

### D. *Solar Thermal Options*

There are two main outputs of active solar technologies: thermal energy (heat) and electricity. Many systems are being designed for cogeneration of thermal and electric energy: Solar thermal systems may produce electricity through the use of heat engines. A variety of solar thermal systems are made possible by varying the number, sophistication, and design details of system components. A simple residential system might contain a flat plate or a tubular fixed collector mounted on the roof. Heated water is transported to a heat exchanger for space conditioning or to a storage tank for later use. One may obtain improvements in energy use and temperature output by concentrating collector systems. Luz uses a parabolic trough design to focus incoming solar radiation on pipes at the foci of the trough, which contains heat-transfer fluid. Solar One—built by McDonnell Douglas Corporation, operated by Southern California Edison—uses an array of movable heliostats (mirrors) to focus sunlight on a central tower-mounted receiver. SolarPlant1—built by LaJet Energy Company, operated by San Diego Gas and Electric—uses a parabolic dish design: Sunlight was reflected onto a single point focus.

Another thermal option is the salt-gradient solar pond. The pond is filled with brine made with one salt or several salts. A salt gradient develops, and the salt concentration varies from a few percent (by weight) at the surface to more than 20 percent at the bottom. Natural convection is suppressed—water at the lower layer is warmer but also has a higher salt content and thus remains heavier than water in the upper layer—and this allows the pond to trap heat in the bottom storage zone. Heat trapped in the storage zone is extracted by heat exchangers for both thermal and electric applications (Lin et al., 1982). Several solar ponds have been constructed in the United States, Australia, and Israel for process heat applications and electric power production. Solar ponds are not yet commercially available, but are economically competitive at certain sites (Bemis and DeAngelis, 1990).

### E. *Photovoltaics*

Photovoltaic (PV) systems, unlike solar thermal techniques, convert sunlight directly into electrical energy. Individual PV cells are made from semiconducting materials such as silicon or gallium arsenide. Small quantities of impurities—e.g., arsenic, boron, or phosphorus—are added to semiconducting materials in layers as positive and negative dopants. The result is termed a homojunction cell, which has solid-state characteristics. Exposing a homojunction cell to sunlight frees electrons within the semiconducting material. This creates a small electric field across the cell by positive and negative dopants, which in turn causes the electrons to flow in an electrical current if the cell is attached to an external circuit. Two other methods for producing intrinsic voltage also exist. Joining two dissimilar semiconductors, such as cadmium sulfide and copper sulfide, produces a heterojunction cell. Joining a semiconductor to a metal forms a Schottky barrier junction. In all three cases, exposing the cell to light creates current.

Researchers are evaluating several alternative methods of obtaining photovoltaic energy. Using hydrogenated amorphous silicon as an alternative to crystalline silicon is being explored. Experiments are under way with alternative semiconducting materials such as germanium, gallium arsenide, cadmium sulfide, cadmium telluride, and copper indium diselenide. Cells made of these alternative materials might be more amenable to mass production techniques since a single crystal would not be needed. Other areas of photovoltaic research have focused on developing thin-film solar cells and cells that can use concentrated sunlight. (More information on these options appears in SERI, 1989.)

Presently, commercial PV systems operate at 10–15 percent conversion efficiencies. In the research arena, some cells have obtained conversion efficiencies ranging between 22 percent in ordinary sunlight and 31 percent in concentrated sunlight (Hubbard, 1989).

### F. *Wind*

One may use wind turbines to provide wind-generated electricity. Systems such as those developed by U.S. Windpower (Gipe, 1989) have provided billions of kilowatt hours of electricity during the past decade. However, wind energy is a variable power source. Reliable electricity from wind requires storage or a backup energy source. Thus, wind energy appears most attractive in remote, windy locations or as an additional source of electricity for the utility grid.

### G. *Near-Term Utility Options*

A tremendous variety of solar technologies currently is under development and study. The economic viability of the solar option is dependent on alternatives: For much of the United States, the chief alternative is power from a utility. Since the National Energy Act was passed in 1978, utilities have begun serving as a market for power as well as a source of power. Utilities such as Southern California Edison have projects under way with a variety of solar thermal, photovoltaic, wind, cogeneration, and other power producers (SCE, 1989). In the near term, two utility-related technologies that have developed rapidly are solar thermal (the parabolic trough systems produced by Luz) and wind (the turbine systems of U.S. Windpower). This paper uses these systems as the reference solar and wind options and compares them with conventional alternatives in section III.

## III. COST ESTIMATES AND COMPARISONS

To facilitate choices among energy options, one needs comparable information on the various system costs. There are three general ways to compare options:

(i) *Generic Comparisons* compare a "general" plant addition with alternatives. Location and utility-specific factors are not detailed.

(ii) *Comparisons With an "Ideal" Utility* add a new technology to an "average" or a theoretical utility system.

(iii) *Utility-Specific Comparisons* evaluate for a particular utility a specific project for its fit into the utility supply plan.

When a utility is assessing new technologies or deciding how to expand capacity, it uses approach (iii). This paper uses approach (i) to provide an overview of technologies and regions. However, one must interpret these estimates with caution, as noted below.

Generic comparisons among technologies have three limitations in addition to the usual difficulties inherent in supply planning analyses for a specific utility. One limitation is the treatment of transmission costs and related issues. Another limitation is a proper accounting for daily and seasonal variation in the value of electricity. A third limitation is the variation in construction time so that alternative technologies provide power over differing time periods.

Specific utilities have contractual access to existing transmission, the location of which can determine the relative merit of specific technologies. Moreover, location may lower transmission costs but increase the costs of fuel delivery. In addition, small utilities frequently contract with larger adjacent utilities so as to integrate the operation of the two utilities. In the latter case, clauses in so-called "integrated operations agreements" can substantially alter the relative economic value of particular technologies (Thomas and Hall, 1990). Generic cost estimates abstract from transmission and related issues.

Temporal variation in demand and the physical characteristics of power plants cause time-dependent variation in the value of electricity. Gas turbines and pumped storage provide rapid access to generating capacity that responds to peak period demand. Gas combined cycle and oil steam generation can be turned off at night, but that affects the cost of energy since the capacity then is idle. Coal and nuclear power cannot be switched off daily and are used to meet base-load power demand during off-peak periods. The value of a particular technology to a specific utility depends on the alternative technologies displaced in the future supply plan relative to the forecast future load and the utility's existing configuration of power plants. The standard analytical method for a utility-specific analysis is called a probabilistic production costing model, typically coupled with a financial model that translates the system generation and construction costs into required revenue (Thomas and Hall, 1990). These complexities influence the choices of particular cost comparisons below.

A lengthy construction period increases financial risk to utilities (Hall and Thomas, 1984) since demand forecasts are less reliable when extended further into the future. Constructing nuclear and coal power plants increases the risk of incurring the cost of excess capacity. Risk analysis requires a utility-specific demand forecast not considered in this paper.

Cost comparisons among alternative technologies require that the power generated from each alternative be available over the same time periods. The projected date for completion of construction must be the same for each alternative compared. Coal and nuclear plants can take 6–12 years to build. The length of construction period affects cost computations. Interest during construction—the carrying cost of capital—is greater for longer construction periods. Historically, construction costs have escalated faster than inflation. Consequently, an assumption that construction for nuclear and coal began prior to the date of analysis will result in understating the cost computations for nuclear and coal. An assumption that construction for solar and wind—which takes less than a year—is delayed until a nuclear or coal plant is nearly complete will result in overstating the cost computations for solar and wind. A generic cost comparison has no satisfactory resolution to this problem.

Table 1 includes an assumed construction cost escalation of 1 percent above the inflation rate, which is slightly less than actual experience during the past two decades. All computations are based on construction commencing in 1990. Column (3) shows construction costs plus interest during construction for municipal utilities (Munis) and investor-owned utilities (IOUs) at interest rates of 7 and 10 percent respectively. For conformity, 1990 is the assumed beginning year of operation for all options even though construction costs show an escalation over the construction period.

Table 1 presents the economic and technical assumptions that determine the outcome of the cost comparisons displayed in figures 1-4. The cost assumptions for nuclear power are from Navarro (1988) and are low relative to other published data (CEC, 1988; Bemis and DeAngelis, 1990). For both coal and gas turbines, table 1 provides four sets of assumptions. Because eastern and western states have substantial variation in coal and gas prices, the assumed prices reflect that variation as shown in column (7). Table 1 presents cost assumptions for coal, gas combined cycle, and gas turbines without new air pollution requirements. It presents cost assumptions for cleaner coal and gas turbine plants, coal fluidized bed, and gas turbine with catalytic converter. The table presents assumptions for the solar parabolic

## TABLE 1
Economic and Technical Assumptions

| | (1) Overnight Construction | (2) Years to Build | (3) Interest Plus Construction 1990 ($/kW) | | (4) Capacity Factor | (5) O&M 1990 (¢/kWh) | (6) Conversion Efficiency BTU/kWh (%kWh/kWh) | (7) Fuel Costs 1990$ / MMBtu |
|---|---|---|---|---|---|---|---|---|
| | | | 7% | 10% | | | | |
| Nuclear | 2,380 | 12 | 4,505 | 5,140 | 58% | 1.16 | 10,200 | 1.10 |
| Coal | 1,400 | 7 | 2,140 | 2,390 | 67% | 0.28 | 10,000 | 1.60<br>-2.00 |
| Coal Fluid Bed | 2,115 | 7 | 2,770 | 3,105 | 70% | 0.30 | 10,000 | 1.60<br>-2.00 |
| Oil | 910 | 5 | 1,255 | 1,365 | 84% | 0.09 | 9,500 | 3.30 |
| Gas Combined Cycle | 670 | 5 | 925 | 1,005 | 84% | 0.35 | 8,600 | 3.00 |
| Gas Turbine | 440 | 2 | 515 | 540 | 10% | 0.17 | 8,000 | 3.00<br>-3.50 |
| Catalytic Converter | 840 | — | 840 | 840 | 10% | 0.5 | 8,000 | 3.00<br>-3.50 |
| Pumped | 855 | 2 | 945 | 985 | 10% | 0.3 | 70% Storage | |
| Wind | 1,250 | 0.5 | 1,270 | 1,280 | 19% | 1.3 | N.A. | N.A. |

## TABLE 1 (continued)
Economic and Technical Assumptions

| | (1) Overnight Construction | (2) Years to Build | (3) Interest Plus Construction 1990 ($/kW) | | (4) Capacity Factor | (5) O&M 1990 (¢/kWh) | (6) Conversion Efficiency BTU/kWh (%kWh/kWh) | (7) Fuel Costs 1990$ / MMBtu |
|---|---|---|---|---|---|---|---|---|
| | | | 7% | 10% | | | | |
| Solar Parabolic Trough | 2,100 | 1.5 | 2,210 | 2,255 | 26% | 1.21 | N.A. | N.A. |

(1) CEC 1985 dollars escalated at 4 percent, except nuclear in 1986 dollars from Navarro (1989), solar from Luz (1989, 1990), and wind from Gipe (1989).

(2) Nuclear from Navarro (1989); coal from LADWP (various years); oil and gas combined cycle assumed; gas turbine, catalytic, and pumped storage from Anaheim municipal; solar from Luz; and wind from Gipe (1989).

(3) The producer price index (PPI) in the *Economic Report of the President, 1989*, rose at 2.6 percent from 1982, while the PPI for capital equipment rose at 1.4 percent, a real escalation of 1.2 percent. Assumed here is 3 percent inflation and 4 percent construction cost escalation. Note the IPD for GNP rose at about 3 percent/year from 1985 to 1989. For nuclear power, construction costs were allocated 2.5 percent for years 1 to 4, 5 percent for years 5 and 6, 10 percent for years 7 and 8, and 15 percent for years 9 to 12. For coal, construction costs were allocated 10 percent for year 1 and 15 percent for years 2 to 7. For gas and oil, construction costs were allocated 20 percent for years 1 to 5.

(4) From Hall and Thomas (1984) except nuclear from Navarro (1989), solar from Luz, and wind from U.S. Windpower (1989). For gas turbine and pumped storage, assume the peak period equals 10 percent of the year.

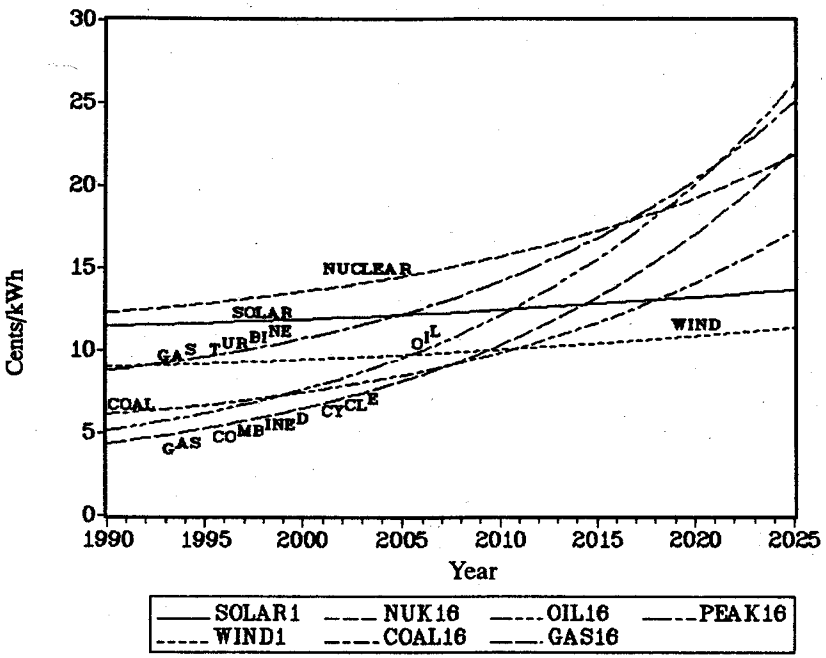
(5) From CEC 1985 dollars escalated at 3 percent.

(6) From Anaheim, LADWP, and Luz.

(7) Oil at 6 MMBtu/Bbl, price of residual oil of $17/Bbl from CEC; West gas at $3/MMBtu, East gas at $3.50/MMBtu; coal at 24.7 MMBtu/ton, delivered price at $40/ton in West, $50/ton in East; nuclear imputed from CEC and Moody's.

FIGURE 1

Interest Rate 10%, Inflation Rate 3%, Fuel Escalation Rate 6%

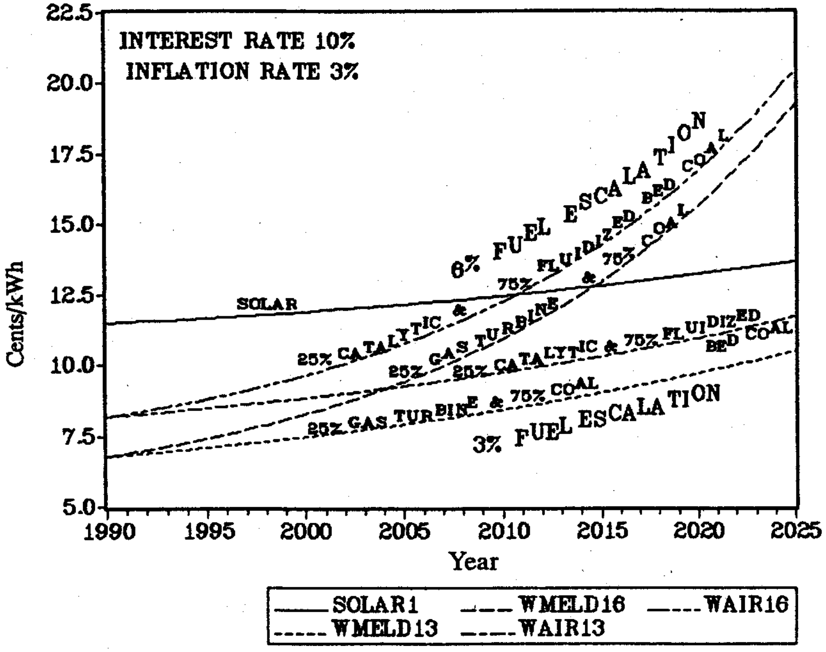


trough technology, derived from cost data from Luz (1989, 1990). Luz uses a gas backup, and the construction costs in this analysis include the cost of the gas boiler. The capacity factor was adjusted to exclude gas from this analysis, however, so that the estimated cost of solar does not reflect the current low price of natural gas.

Figure 1 differs substantially from the other figures in that it does not reflect temporal variation in the value of electricity. For example, solar power costs less than nuclear power over the respective lives of the plants. Moreover, solar power is more valuable since solar facilities generate electricity during peak and mid-peak periods while nuclear facilities generate mostly during the off-peak period. For example, Pacific Gas and Electric (PG&E) defines 60.5 percent of the calendar year as the off-peak period. Wind power costs less than solar power but is less valuable since a substantial portion of wind power is generated during the off-peak period. In San Gorgonio Pass, Calif., 61.8 percent of the power from wind is generated during the off-peak period.

FIGURE 2

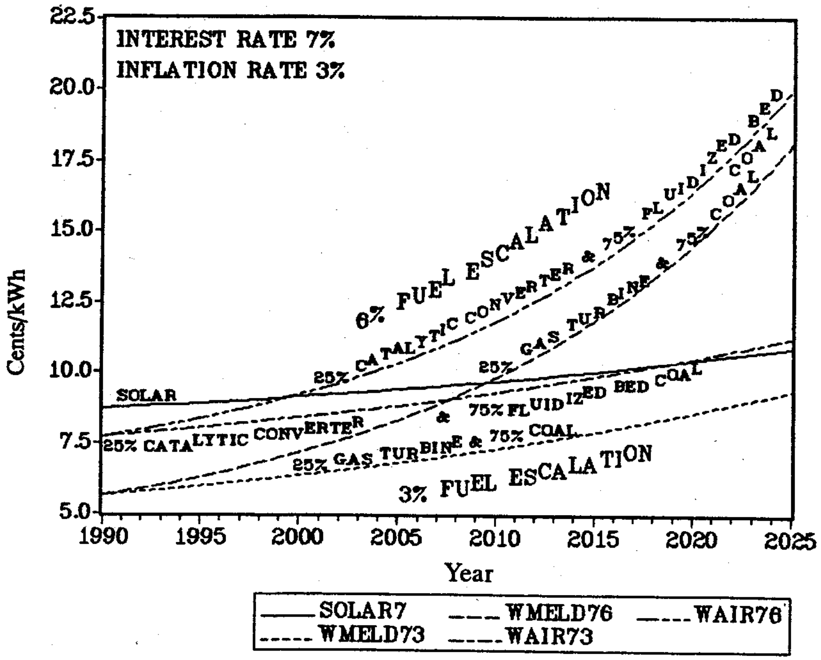
Western U.S. Investor-Owned Utilities



Solar power is not directly comparable with any specific technology in figure 1 since the power is generated during the peak and mid-peak periods. As an example, the cost curve of gas combined cycle is predicated on an 84 percent capacity factor, a baseload power plant. Relegating the plant to peak and mid-peak periods reduces the capacity factor to 35 percent. This would substantially shift the cost curve upward. Solar facilities generate about 25 percent of their output during the peak period and 75 percent during the mid-peak period. Figures 2 and 3 compare solar power in the southwestern United States with alternative melded averages of gas turbines and coal using 25 percent and 75 percent as weights, respectively.

Power production from wind in the San Gorgonio Pass occurs during peak, mid-peak, and off-peak periods—as defined for PG&E—6.6, 31.6, and 61.8 percent of the time, respectively. This power production mirrors the defined percentage of the calendar year during these periods, given as 6.0, 33.5, and 60.5 percent, respectively. Wind power facilities produce electricity equally during each period in a manner similar to that with a baseload power plant. Power from wind arguably may be as reliable as that from nuclear plants but

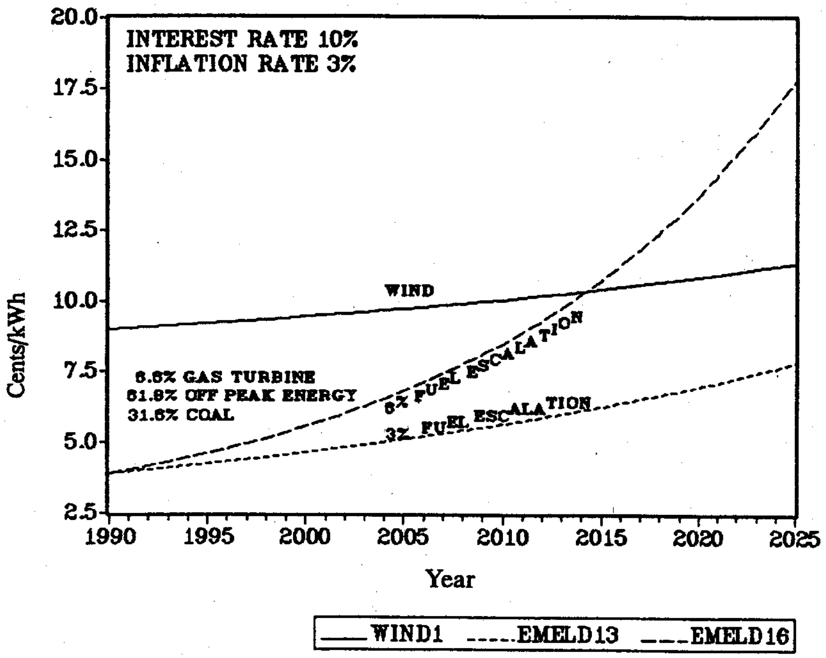
**FIGURE 3**
Western U.S. Municipal Utilities



not as reliable as power from coal plants. Figure 4 compares the cost of wind with a melded average of the following: a gas turbine for 6.6 percent of peak power, a coal plant including capital cost for 31.6 percent of mid-peak power, and the short-run operating cost of off-peak energy for 61.8 percent of off-peak power. Because nuclear plants are lower on the dispatch order than are coal plants, figure 4 uses the cost of power from a coal plant as the cost of off-peak energy.

The portion of total cost attributable to construction relative to the cost of fuel determines the flatness in figures 1-4. The flattest curves—for solar and wind—are the most capital-intensive technologies, followed by nuclear, coal, oil, and gas, in that order. All computations include operation and maintenance costs rising at a rate equal to the assumed 3 percent general inflation rate. The ascent of the fuel-intensive technologies depends on the fuel escalation rate. A 6 percent fuel escalation rate equals a real escalation of 3 percent above inflation. If one assumes a 3 percent real escalation of fuel above inflation, then all cost curves cross those for wind and solar power—except nuclear, which always is higher. This means that fossil fuel-based technologies (gas, oil, coal) are less expensive during the early years of operation, relative to solar and wind, but are more expensive in the later years.

**FIGURE 4**
Eastern U.S. Investor-Owned Utilities



Interpreting the year when curves cross as the year when a technology becomes economic is incorrect. The least-cost technology is the one with the lowest present value of the cost stream over time. The further into the future, the greater the effect of discounting. As a rough rule of thumb, solar or wind is the lowest cost if the alternative cost curve crosses and becomes higher sometime before one-half of the plant life—i.e., before the year 2007.

Solar power is capital intensive, and Muni's have a lower cost of capital. One can see the effect of the cost of capital by examining the difference between figures 2 and 3, a comparison showing the relative advantage Muni's have over IOUs for solar power. Both figures 2 and 3 show the favorable effect of more stringent future air pollution regulations on the cost comparisons with solar power. Figures 2-4 show the effect of alternative assumed future fuel escalation rates on the cost comparisons with solar and wind.

## IV. KEY FACTORS AND POLICY CAVEATS

Subject to the assumptions and caveats in section III, the material in that section suggests several results:

(i) Solar energy clearly is cheaper than one alternative—nuclear power.

(ii) For other options, the comparison does not result in robust conclusions but depends on several key factors: relative prices, escalation rates, and capital costs. For example, if one ignores costs to the environment, then windpower appears viable in eastern utility applications only at the higher fuel escalation rates.

Solar technologies appear to have significant potential. However, that potential is based on several assumptions. One of the most important appears to be regional differences—in costs of alternatives, in the regulatory environment, in resource availability. An option can be either competitive or outside consideration according to regionally varying factors discussed below.

### A. *The Status of Alternative Energy Options*

Many solar energy costs depend directly on the solar energy industry, but the desirability of owning or operating a solar energy system is crucially dependent on the range of non-solar options available to energy users and suppliers. In many areas of the country, relatively cheap and abundant fossil fuel-based energy supplies have greatly slowed solar energy research and usage during the past seven years.

There has been one major exception, resulting from an interesting combination of prices and legislation. The Public Utilities Regulatory Policies Act (PURPA), a portion of the 1978 National Energy Act, guaranteed a market for the electricity generated by independent producers. Contracts between utilities and these independent qualifying facilities (QFs) guaranteed a specified purchase price per kilowatt hour of electricity generation for a 10-year period. The guaranteed price reflected forecasts of fossil fuel costs. The PURPA also allows up to 25 percent of the energy generated from a facility to come from natural gas. In California, the California Public Utilities Commission set up "Standard Offer No. 4" (SO4): The 10-year price guarantee was based on 1983 oil price forecasts. The 1983 forecasts did not anticipate the slump in oil and gas prices in 1986. SO4, plus the ability to buy and use natural gas at prices lower than the forecast prices, resulted in some "gas arbitrage": Natural gas would be purchased cheaply by QFs, used to generate 25 percent of the electricity output of the facility, and sold to utilities as electricity at guaranteed prices. (For example, the Luz system has a 35 percent capacity factor, which includes the use of gas. The cost calculations depicted in figures 1–4 for solar power are exclusive of gas, as reflected in the lower 26 percent capacity factor in table 1.) This arbitrage has been possible at solar thermal and cogeneration facilities that use fossil fuels but not at facilities such as photovoltaic systems, which produce electricity directly from solar radiation. Thus, thermal systems received a strong development incentive while systems that produced electricity directly did not.

The SO4 contracts reduced financial uncertainty to solar investors and reduced economic uncertainty to utilities. Because the prices were guaranteed to QFs for 10 years, QFs were able to attract investors more easily. Utilities faced less uncertainty over the cost of power from QFs. For example, if fossil fuel prices had risen faster than the forecasts, then the QFs would not have been able to raise their prices accordingly.

### B. *The Existence of Tax or Other Incentives*

Tax and subsidy considerations are another major force in market choices among energy alternatives. Taxes and tax reduction measures, such as investment tax credits or depreciation and depletion allowances, will change the perceived cost of using energy resources. Smith (1989) notes that private purchases of photovoltaic systems declined markedly after 1986, when federal and state governments eliminated previously applicable tax credits.

### C. *Environmental Concerns*

One key reason for a renewed interest in alternatives to fossil fuels may be the stringent environmental standards under consideration in several regions. Many areas are unable to meet the standards of the Clean Air Act without significant changes in the use of fossil fuels. A variety of alternative fuels, processes, and policy options are under consideration.

Walton and Warren (1982) listed several policy options affecting solar energy usage and a set of criteria for evaluating alternative policy options:

—Reduces uncertainty
—Encourages innovation
—Promotes efficiency
—Reduces capital market problems
—Encourages equity
—Promotes conservation
—Is inexpensive to undertake.

Given the experience of the past decade, what policy options appear most promising for the future?

One major lesson learned is that not all subsidies are the same. Tax credits tend to promote hardware development. This may reduce uncertainty but also may lead to a large number of abandoned projects when the credits end. The subsidy provided through SO4 has been an alternative type of subsidy—much like a matching production grant—and seems to have quite different results. Under SO4, the solar energy producers had an incentive to innovate, to explore alternative energy options, and to develop the alternative energy industry. SO4 contracts reduced uncertainty to both the utilities and the QFs. Even in the face of a slump in the prices of fossil fuels over the past five years, solar and wind industries were able to continue cost-reducing technological advances. These alternatives are now viable options that mitigate national security risks from increasing dependence on imported oil and show promise of helping to deal with environmental concerns.

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