# THE HELIOS STRATEGY: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet

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# FOREWORD

In 1973, shortly after it was founded, the International Institute for Applied Systems Analysis embarked on a major study of energy supply and demand looking to the year 2030 and beyond. The central findings of this program have now been published: The Energy Systems Program Group of IIASA, Wolf Häfele, Program Leader, *Energy in a Finite World: Volume I. Paths to a Sustainable Future; Volume II. A Global Systems Analysis*, Ballinger, Cambridge, Massachusetts, USA, 1981.

This work began with the idea of understanding, from an optimistic point of view, various models of energy supply by stretching them to their physical limits. There are, of course, many nontechnical constraints that prevail and, indeed, act as determinants of what will happen – but our idea was to understand what would be foreclosed when such substantive opportunities are not permitted to materialize. From this point of view we looked into coal, nuclear, solar, and renewable sources of energy supply.

Jerome Weingart's contributions to this approach early in our energy program's work were major. He applied its concept in a study of the features and potential of solar power, and his results had a strong influence on the thinking of the energy program's workers.

The paper reproduced here reports the findings of Dr. Weingart's work on solar energy for us. It was first presented publicly at the 1977 Alternatives to Growth Conference at Woodlands, Texas, sponsored by the Woodlands Conference, where it won the $10,000 Mitchell Prize. We are indebted to the Woodlands Conference for permission to reprint it.

Readers interested in a comprehensive list of publications supporting the findings of IIASA's Energy Systems Program will find it in the second of the two volumes cited above. A selected list of the more important items appears at the end of this report.

WOLF HÄFELE
*Leader*
Energy Systems Program

# The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet

JEROME MARTIN WEINGART

**Editor's Note**

In a previous issue (Vol. 12, No. 1), we presented one of the papers awarded the $10,000 Mitchell Prize at the October 1977 "Alternatives to Growth" Conference at The Woodlands, Texas. We have the privilege in this issue to offer our readers another of the prize winners, Jerome Weingart's "The Helios Strategy." I am sure they will agree that the honor was richly deserved.

ABSTRACT

Over the next hundred years there must be a worldwide transition from reliance on fossil fuels to the use of some combination of long-term and abundant primary sources for the production of heat, electricity, and synthetic fuels. The rate at which such options can be developed and employed, as well as the maximum rate at which they can provide energy at a sustained rate, will place important constraints on the rate and limits to growth of other human activities. It is generally argued that only the fission option, in the form of the fast-breeder and high-temperature reactors, can provide the energy required for a livable world, particularly if this means a world of 10 billion people living at the present energy level of Western Europe. However, a careful examination indicates that the use of solar energy, through a menu of technological options, can provide the needs of a world at this scale of energy use, and that this can be accomplished within the constraints of land availability and requirements for energy, materials, and labor. No scientific breakthroughs are required, although a number of these would be helpful, but very substantial engineering advances *are* required, and the transition to such a world-wide system would take no less than a century. However, the feasibility of such large-scale use of solar energy will substantially alter those aspects of the "limits to growth" discussions in which future growth strategies are constrained by available and acceptable energy alternatives. This paper outlines a global solar-energy system considered feasible for more than 10 billion people living at 5 kW per capita.

## Energy, Well-Being, and the Transition to a Post-fossil Fuel World

Energy is a central issue in present discussions of the "limits to growth." In much of the world, the growing disparity between rich and poor is closely related to a gap in the amount and thermodynamic quality of available energy and the efficiency with which it is used [9, 36]. One dilemma is that modern technology and abundant energy, which together could help to erase much of this disparity, constitute in their use a major source of environmental disruption [35]. A great challenge to our technological and social ingenuity

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This paper was presented at the 1977 Alternatives to Growth conference held at The Woodlands, Texas. An edited version will appear in Dennis Meadows and Marion McCollom, Eds., *Alternatives to Growth—II*, Ballinger Publishing Co., Cambridge, Mass., 1978.

**TABLE 1**

**Present World Use and Reserves of Traditional Fossil and Renewable Energy Resources**

| | TW(th)[a] | TW(th)–year |
|---|---|---|
| Oil and natural gas[b] | 5.3 | 400–800 |
| Coal[c] | 2.3 | 2000[b] |
| Hydropower | 0.6 | renewable |
| Wood[d] | 0.3–1 | renewable |

[a] 1 TW = $10^{12}$ W.

[b] Secondary and tertiary recovery possibilities not adequately included in these estimates.

[c] WAES: ~1/5 of all coal in place assumed ultimately recoverable. (WAES is an abbreviation for Workshop on Alternative Energy Strategies; see Wilson, [78]).

[d] Primarily noncommercial uses.

will be the navigation of the transition to a world in which we can operate well within the carrying capacity of natural systems and at the same time extend justice, equity, and a first-class environment to all.

The momentum in world population growth, the aspirations of the developing world, and the continuing (but probably slower) future growth of the industrialized world suggest an almost inevitable increase in global energy use over the coming century. Present consumption (Table 1) of primary energy resources is 8 TW(th), of which 4 TW(th) comes from oil and almost 2 TW(th) is from natural gas [1 TW = $10^{12}$ W]. Growth in primary energy use at an average rate of 2% per year would result in a demand for 22 TW(th) in 50 years and 60 TW(th) in 100 years (Table 2); extreme reduction to 0.9% per year leads to 13 TW(th) demand by 2027 and 20 TW in 2077. This 20 TW(th) might correspond to a

**TABLE 2**

**Present Situation and Three Scenarios for Growth of Total Primary Energy Production**

| | | Projected world energy demand[a] | | Scenarios for 2077 | |
|---|---|---|---|---|---|
| Scenario | Growth rate | 2027 | 2077 | World population | Per capita energy use [kW(th)] |
| 1. Low | 0.9% | 13 | 20 | $6 \times 10^9$ | 3.3 |
| 2. Medium | 2.0% | 22 | 58 | $10 \times 10^9$ | 6.0 |
| 3. High | 3.3% | 41 | 200 | $20 \times 10^9$ | 10.0 |
| | | | | 1977 | |
| Present situation[b] | 5% (2.0%) | 8 | | $4 \times 10^9$ | 2.0 |

[a] Terawatt (th) rate of mobilization of primary sources in thermal equivalent terms.

[b] The higher growth rate has prevailed over the past several decades; long-term average for past 150 years, including use of wood, is 2%.

**TABLE 3**

**Characteristic Time[a] to Exhaust Known Fossil Resources**

| Resource[b] | Reserves TW(th)-year | Characteristic time (years) at various growth rates 0% | 1% | 2% | 3% | 4% |
|---|---|---|---|---|---|---|
| Oil and gas | 400–800 | 50 | 41 | 35 | 31 | 27 |
| | | 100 | 69 | 55 | 46 | 40 |
| Coal | 2000[c] | 250 | 125 | 90 | 71 | 60 |
| Oil, gas, and coal | ~3000 | 375 | 156 | 107 | 84 | 69 |

[a] $T = g^{-1} \ln [1 + Rg/P_0]$, where $g$ = growth rate; $R$ = reserves in TW(th)-year; $P_0$ = 8 TW(h); $P(t)$ = rate of primary energy consumption (assumed exponential) = $P_0 \exp(gt)$.

[b] WAES [72].

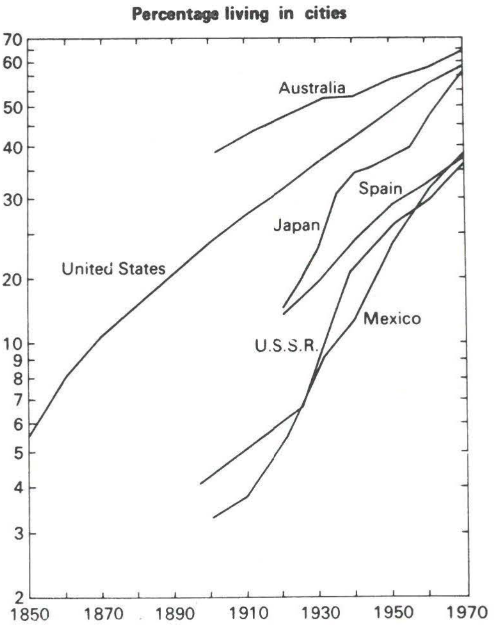
[c] Twenty percent of total in-place coal reserves (10,000 TW(th)-year) assumed recoverable.

world of a stable population of 6 billion and a per capita energy use of 3.3 kW(th). If annual growth could be sustained at 3.3%, less than the 5% of the past five decades, demand would be 200 TW(th) by 2077—the technological optimist's fantasy of a world of 20 billion people living at the present U.S. per capita energy-consumption level.

Realizing even the most modest growth scenario will be complicated by increasing prices, a peak in production around 1990 and resource depletion in the coming half century for oil and natural gas [71]. The far greater amounts of coal (Table 3) geologically in place, even if they could be fully mobilized, would be exhausted in roughly a century. More realistic estimates [29] suggest that as little as 15–25% of this geophysical reserve can actually be used. Over the coming century there must therefore be a transition from traditional fossil fuels to interim resources (expensive, nontraditional fossil fuels and uranium in nonbreeder reactors) and to long-term, large-scale sources (the fast-breeder reactor, fusion, geothermal energy and solar energy). Regardless of the eventual mix of energy sources and technologies, the secondary energy of the future will almost certainly be expensive by present standards, and its availability will be constrained by social [25, 26], environmental, economic [37], and possibly even technical factors, rather than resource availability. The rate and scale of this transition will vary from place to place, depending on the wealth, resources and industrial development of the region, but it will occur globally, and it will be essentially completed within a century or so.

This transition will be constrained by other evolutionary changes in the human environment. Over the past century the industrialized nations have experienced an unprecedented and seemingly inexorable demographic shift toward urbanization [17], with a quarter of all people and well over 50% of the population of most developed countries now living in cities of 100,000 or more (Fig. 1). Human settlements themselves are becoming increasingly complex, technological, dense, and spatially extensive [67]. Doxiadis and Papaioannou [20] argue that this trend will continue through the evolution (Fig. 2) of settlements such as the great urban "dynopoli" of Japan, Europe, and North America, and the final emergence of a global network of settlements of continental extent: "Ecumenopolis" (Figs. 3–6).

The infrastructures that provide water, energy, communications, and other services have also grown more complex and extended. In particular, large settlements increasingly require secondary energy forms of high energy density and high thermodynamic quality,




Courtesy of Scientific American, New York, N.Y.

**Fig. 1. The demographic shift towards urbanization [17].**

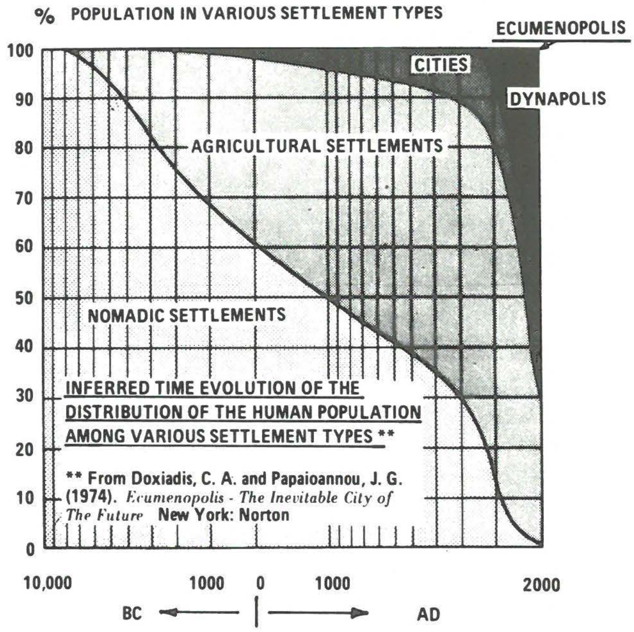



**Fig. 2. Inferred time evolution of the distribution of the human population among various settlement types [20].**


Courtesy of W.W. Norton & Company, Inc., New York, N.Y.

**Fig. 3. Ecumenopolis 2100 [20].**

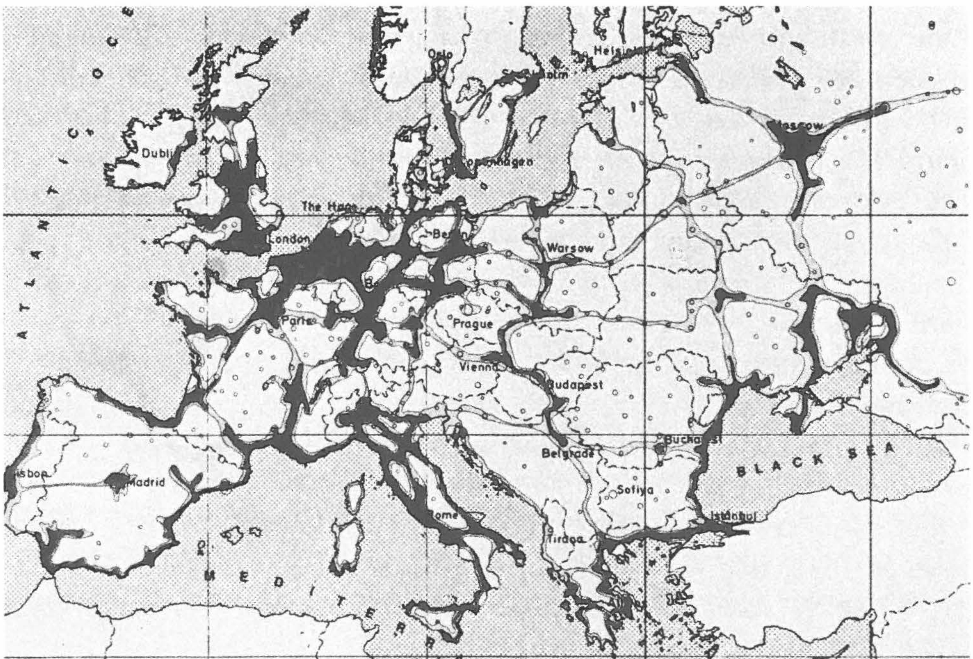



**Fig. 4. Ecumenopolis 2100 [20].**

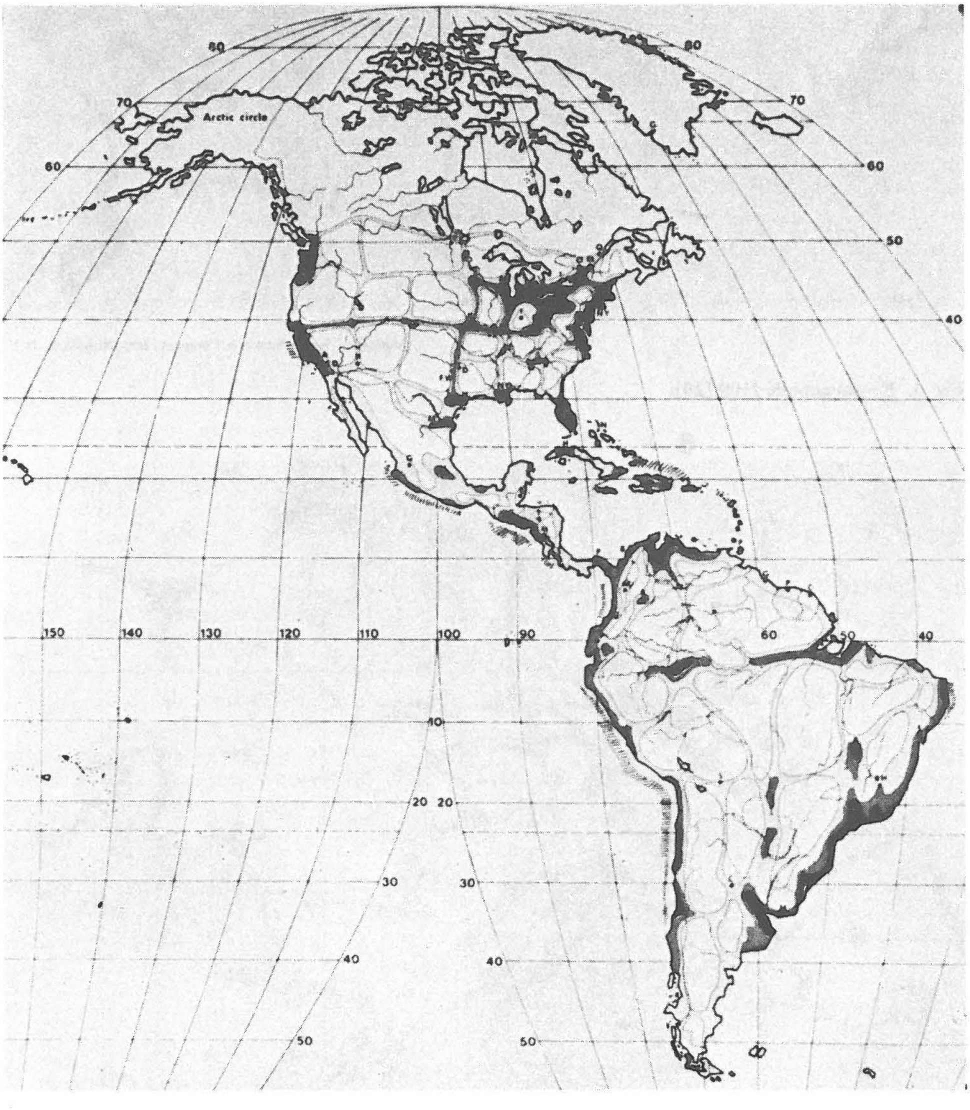



Fig. 5. Ecumenopolis 2100 [20].

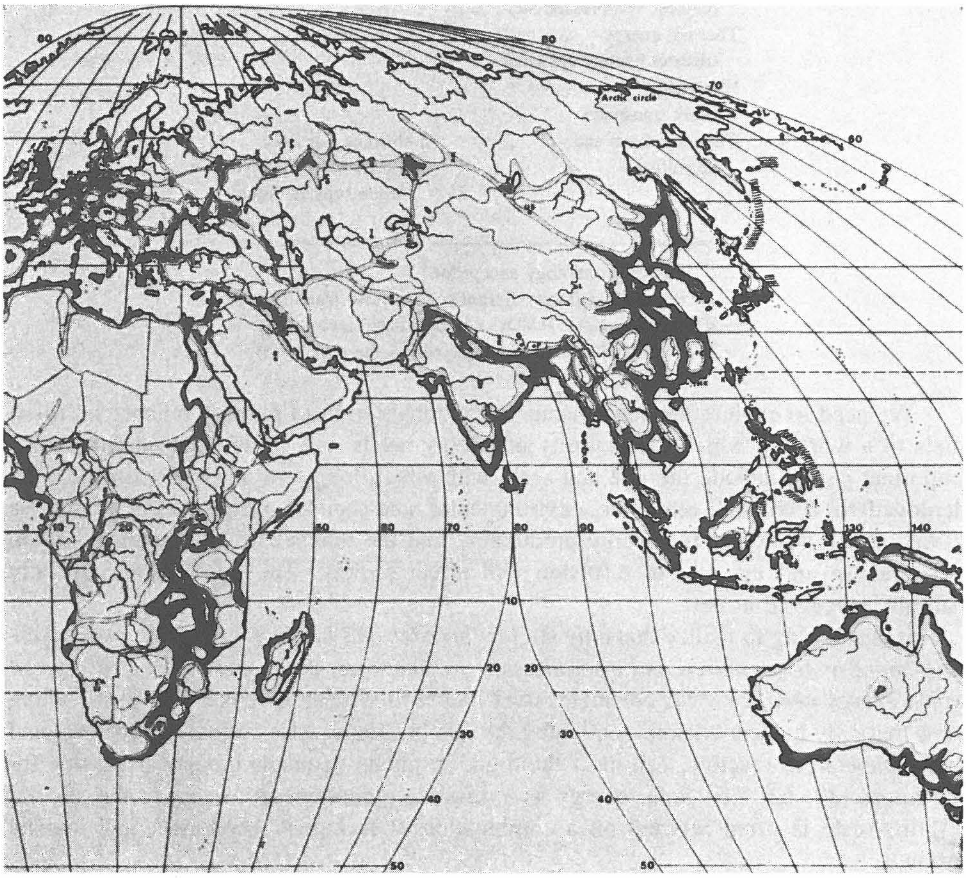



Fig. 6. Ecumenopolis 2100 [20].

amenable to economic and efficient transport and conversion. These are primarily electricity and gaseous and liquid fuels. Growing transportability of secondary energy (Table 4) permits correspondingly large units for conversion of primary energy to secondary forms [48] and at the same time allows the siting of these facilities, whether for social, environmental, economic, or logistic reasons, at considerable distances from major demand centers. Secondary energy networks also decouple primary energy sources from end use, facilitating the flexible evolution of a mix of new energy sources. This conjunction of urbanization, settlement evolution, and transition to secondary energy carriers requires that the interim and long-term energy forms, if they are to provide a substantial share of future energy needs, *must be converted on the necessary scale to these secondary carriers.*

**TABLE 4**

**Transportability of Secondary Energy (km)[a]**

| | |
|---|---|
| Mechanical energy (cables, compressed air) | 1–10 |
| Thermal energy (district heating systems) | 10–50 |
| Electricity[b] (bulk transport) | ≤5000 |
| Chemical fuels and negentropy | 5000 (gas pipeline) global (liquid fuels, negentropy as liquid air) |

[a] Present technology except for [b].

[b] Present average distance for bulk transport is ~100 km. Present HVDC transmission technology is ≈3000 km (5000 km can be expected by the year 2000).

We need to explore the consequences of a transition from primary reliance on fossil fuels to a world in which the majority of energy needs will come from other sources. Important issues include the rate and scale with which long-term energy options can be deployed; the technical, economic, environmental, and social consequences of alternative technological strategies for energy production; and the manner in which constraints on ultimate use and the rate of diffusion will affect society. The implications are only partially perceived at best.

It is sobering to realize that *only the fast breeder and harnessing the sun are technically more or less assured and also adequate to meet even the most modest of projected world energy needs over the coming century and beyond.* Yet there is a widely prevailing view that only nuclear fission, combining the fast-breeder reactor with the light-water and high-temperature reactors, can meet the high, sustained demands thought necessary for the future [30, 63, 72]. Solar energy as a possible global energy source at the 10–100 TW(th) scale is often rejected on a combination of technical, economic, and logistic grounds.

Others [33, 43, 44, 56] argue that in the United States and other industrialized nations, energy demand can in fact decrease through a transition to more energy-efficient lifestyles and through rapid diffusion of solar and geothermal technologies employed on an individual scale much smaller than the integrated electrical and fuel networks of the present. Still others [49] have suggested the possibility of a global solar-energy network. This wide divergence in viewpoints will persist for a very long time, reflecting substantial uncertainties in important economic, technical, social, and environmental aspects of various energy strategies, coupled with widely differing personal philosophical viewpoints.

## Sunlight as a Global Energy Resource

I propose an alternative to the views that "small is beautiful" or "large is necessary"—one that is curiously compatible with either and appears resilient to the considerable uncertainties of the turbulent transitional era we have entered. Analysis suggests that sunlight could eventually be the primary and even exclusive source of heat, electricity, and synthetic fuels for the entire world, continuously and eternally on a scale (>100 TW) generally regarded possible only with fusion or with fission via the fast breeder (Table 5). It appears that this can be achieved through a global network of solar-conversion facilities coupled with appropriate energy-transport and storage systems, and that this is possible within acceptable constraints on energy payback time, capital investment, and available suitable land. The environmental and social consequences, though not negligible, appear far less problematical than those likely with fission [38] or (if ever available) fusion alternatives [31]. Most significantly, such a solar energy system has attributes that could facilitate a far safer, more stable world than seems possible with the fission options.

**TABLE 5**

**Energy Production from Renewable and Large-Scale Energy Sources in the Asymptotic Phase**

| Source | Production rate TW(th) |
|---|---|
| Tidal | $\ll 1$ |
| Geothermal | $\approx$1–5 |
| Fission (FBR) | >100 |
| Fusion | >100 |
| Solar: | |
| Indirect | 10–20 |
| Direct | >100 |

Naively, sunlight seems an ideal source of energy. The source itself is eternal and unchanging; the resource is globally distributed, not subject to embargo or depletion, and is of sufficient thermodynamic quality to produce at high efficiency the heat, electricity, and synthetic fuels required by a technologically advanced society. On the other hand, sunlight has characteristics that make it problematic to convert and use reliably and economically. Difficulties include the diurnal and seasonal cycles, the unpredictable effects of weather, the nonstorability of the energy in its primary form (photons), and the "low" power density of the direct radiation. A further difficulty is the lack of a practical technology for truly large-scale seasonal electricity storage.

Technically, but at a price, these difficulties can be resolved by a suitable network of solar energy conversion systems. (Some of the important characteristics of these are summarized in Table 6.) In an asymptotic state, this "network" could be a richly structured set of systems ranging from very small, localized units to very large complexes,

**TABLE 6**

**Secondary Energy Production from Solar-Energy Conversion Systems**

| Resource | Technology | Efficiency[a] | Ground cover | Secondary energy | W(th)/m² dedicated land, sea | W/m² solar machine |
|---|---|---|---|---|---|---|
| Direct beam 7–8 kWhr/m²-day 290–333 W/m² | STEC | 0.15–0.25 | 0.4–0.6 | electricity | 50–150 | 44–83(e) 130–250(th)[b] |
| | ST-$H_2$ | 0.20–0.60 | 0.4–0.6 | hydrogen | 24–120 | 60–200(th) |
| Global radiation 2–6 kWh/m²-day 83–250 W/m² | solar heating | 0.20–0.35 | N/A | low-grade heat (<100°C) | N/A | 20–90(th) |
| | biomass (existing) | 0.01–0.03 | 0.9 | biomass, fuels | 0.7–7 | 0.8–7.5(th) (cultivated area) |
| | new biomass, biochemical | 0.05–0.15 | 0.8 | fuels | 3–30 | 4–40(th) |
| Global or direct | photovoltaic | 0.10–0.25 | 0.4–0.9 | electricity | 10–216 | 8–80(e) 24–240(th) |
| Ocean thermal gradients | OTEC[d] | 0.03 | 4 plants/ $10^3$ km² | elec., fuels, lair | 9(th) 3(e) | N/A |
| Wind | wind | 0.60 (max.) | 0.01–0.05 | electricity | 3–15(th) 1–5(e) | 90(e)[c] |

[a] Conversion from the resource to secondary energy.

[b] 1 kW(e) is assumed equivalent to 3 kW(th).

[c] The secondary energy production rate from wind machines will increase as the swept diameter of the machine increases. This example is for the 100 kW(e) U.S. wind turbine developed by NASA. It has a 38-m swept diameter and produces 100 kW(e) in a wind of 8 m/sec. Downstream spacing is assumed to be 10 blade diameters, adjacent spacing 2–10 diameters, depending on the directional variability of the wind.

[d] 30 km²/100 MW(e).

producing electricity and synthetic fuels, with interconnection over thousands of kilometers. A richly articulated hierarchical structure, loosely analogous to a complex ecosystem, could provide a stability and resilience [39, 73] that may not be possible with other long-term options, which provide for energy conversion only at very large scales of production and system complexity. This global system would exhibit the following features:

1. Local use of solar-generated heat for space heating, water heating, and industrial processes where economically and logistically suitable.
2. Local and regional use of small-scale mechanical, electrical, and fuel-generating units, especially in developing countries.
3. Solar electric power plants of various sizes located throughout the world, primarily in sunny regions, interconnected through large integrated electric utility systems over distances up to several thousand kilometers.
4. Solar fuel generation units primarily in sunny regions and interconnected globally via pipeline and, for a few locations (Japan), by tanker (cryogenic or liquid fuel).

In particular, the large-scale generation of hydrogen and of liquid fuels would permit, through long-distance energy transport and seasonal energy storage, the complete decoupling in space and time of the solar source and energy needs. Liquid fuels such as methanol could be produced by combining the hydrogen with carbon from coal or directly from the atmosphere or ocean. Already electricity can be transmitted several thousand kilometers with low losses (5%) via high-voltage dc transmission, permitting the linking of geographically dispersed solar power plants within larger integrated electrical networks. This system integration of dispersed solar generating capacity can substantially increase the reliability of solar units relative to any one specific site [1, 65]. Hydrogen can be transported over continental distances of 5000 kilometers or more, with available or developable pipeline system technologies. Hydrogen, widely regarded as the gaseous energy carrier of the future [8, 68], can be used to run virtually all of the activities of an industrial society with only minor changes in technological infrastructure, and could become the universal medium to decouple primary energy sources from the end use. In fact, large-scale production of hydrogen coupled with the successful development of commercially interesting fuel cells could permit efficient production of electricity and heat on the scale required at or near the end user, possibly leading to the eventual disappearance of large-scale electric power plants and transmission lines. In any case, production of hydrogen or some other globally transportable synthetic fuel from solar and fission energy is essential if these are to emerge as global energy resources.

This simple picture has a certain internal consistency. First, for solar energy to provide a substantial fraction of world energy needs, the production of electricity and synthetic fuels is essential. Solar thermal techniques, including water and space heating as well as process heat, can displace at most 5–10% of the primary energy use in industrialized countries and are likely to displace even less in much of the tropical, semitropical, and arid parts of the developing world.

Second, the scale of future energy use, even in the most modest scenarios and using the most efficient of solar technologies, will require substantial land areas (Fig. 7). Yet in spite of competing pressures for land from increasing food demands, urbanization, and the needs for forests and the maintenance of ecological diversity, the arid sunny wastelands of the globe—some 20 million square kilometers—will remain essentially unused and potentially available for large-scale use, even in an ecumenopolis of 20 billion people [20].

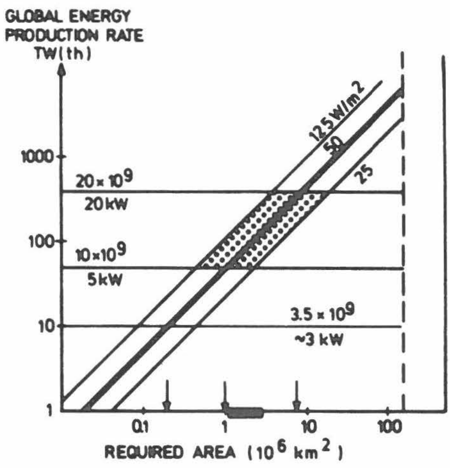



Fig. 7. Solar energy area requirements.

Third, the price of solar-derived energy will be (approximately) inversely proportional to the magnitude of the available solar resource. For direct conversion technologies, this means that the least expensive secondary energy production will be in the sunniest regions; for those technologies (solar thermal electricity, solar thermochemical production of hydrogen) that respond only to direct beam sunlight, location in arid, sunny regions will be essential.

Long-distance transport permits such a siting strategy. All of Europe is within practical high-voltage transmission distances of Portugal, Spain, and Turkey; in a few decades undersea cable from North Africa could also bring solar electricity to Europe. With the exception of Japan, which must be served by liquid fuels via tanker, virtually the entire world is within practical hydrogen pipeline transport distances (5000 km) of large regions of arid, sunny land.

Economic considerations also support such an approach. Under optimistic but not unreasonable assumptions, the production of hydrogen from sunlight by thermochemical conversion in desert regions would cost about $40 per "barrel" (equivalent oil costs). Production using the same technology in Central Europe and climatically similar regions would cost approximately $150 per barrel. However, 5000-km hydrogen transport using 48-in. pipeline would cost about $3 per barrel [8, 19, 28] and the use of geophysical storage would add approximately $1 per barrel (Fig. 8).

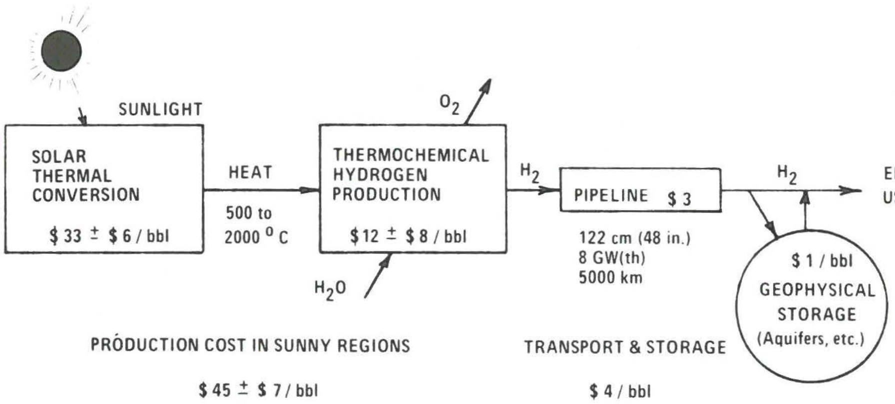



**Fig. 8. Large-scale solar thermochemical fuel logistics. Both distributions taken as Gaussian; total uncertainty determined by convolution of the two distributions.**

Hydrogen would be stored for short periods (up to several years) in aquifiers and for longer periods (decades to centuries) in natural formations including depleted oil and gas fields. In Europe the presently identified gaseous energy storage locations would permit storing up to several years of present Western European energy demands.

The asymptotic *mix* of solar technologies would depend in part on the required total rate of secondary energy production. The use of indirect forms of sunlight (hydropower, ocean thermal gradients, wind, and waves) appears limited to something on the order of a few tens of TW(th) at most (Table 7), and some argue that wind, waves, and OTEC combined are unlikely ever to contribute more than a few TW(th) [72]. Low-efficiency direct conversion, notably biomass production, may be limited to a few terrawatts because of competition with other land uses. Only the high-efficiency direct conversion options appear to have the potential for practical energy supply of 20–100 TW(th) or more, comparable with the potential from the fast breeder and fusion.

**TABLE 7**

**Potential Scale of Solar Energy Conversion (TW(th))**

| | Present use | Practical maximum | Physical maximum |
|---|---|---|---|
| *Indirect forms:* | | | |
| Hydropower | 0.9 | 5 | 9 |
| Wind | — | 1–10 | 10 |
| Waves | — | <1 | 1 |
| Ocean currents | | ? | ? |
| OTEC | | | |
| Near-shore | — | 0.1 | <0.5 |
| Deep ocean | — | 1–10 | ≈100 |
| *Direct conversion:* | | | |
| High efficiency direct conversion to electricity and fuels | | ≈100 | >100 |
| Biomass (noncommercial) | 0.3–1 | <10 | <100 |
| *Tidal:* | — | ≪1 | 3 |

A global transition to such a solar energy system, if it is possible, would require a century or more. Urbanization of the human population is expected to continue during this period and the fraction of the world population potentially served by such extensive technologically sophisticated energy networks would increase.

For Northern and Central Europe, economic considerations, the intensity of local land use and the long periods of little sunlight (especially direct beam radiation) mean that solar energy can be a significant energy option only if the electricity and fuels are made elsewhere. A solar development program could emerge in which these technologically advanced, but sun-poor nations in Europe form partnerships with sun-rich neighbors. For example, a technical and economic partnership between West Germany and Portugal for large-scale thermochemical hydrogen production, to be shipped throughout Europe and stored underground may be more sensible than an analogous nuclear-based relationship with Brazil. In such partnerships the industrialized nations would initially provide technological and managerial skills and investment capital, and the developing host regions would also obtain high-quality energy required for their development. Such a pattern of alliances, if proliferated globally, could provide far more equitable and useful transfer of capital and capabilities as well as a much greater opportunity for real development in the less developed countries (LDCs) than possible within the present international petroleum system or the present approach to the development of fission power systems.

Like nuclear power, giant solar technologies might appear to benefit primarily the urban areas, but unlike nuclear systems, many solar units can produce electricity and fuels with smaller units without substantial economic penalties. Small (tens to hundreds of kW) solar-powered Stirling generators for irrigation and electricity will cost almost the same per kW(e) (within present uncertainties) as 100 MW(e) central receiver systems STEC units [14].

Energy systems could be tailored to match the needs and structures of a wide variety of communities around the world. As communities grow in size, wealth and technical sophistication their energy systems could "organically" grow in adaptive response. The change would clearly be synergistic among the elements of increasing wealth, technical sophistication, and organizational capability. Such development might also be far more amenable to local control and management, even with growth and eventual coallescence of local systems into much larger systems, than would be possible with development "from the top down," the only option possible with energy technologies that have an inherently large unit size.

In fact, one authentic beauty of many solar options, since the individual units and systems can be quite small, is that they do not require sophisticated, complex organizations for installation and operation. Rural people have demonstrated enormous skill in maintaining automobiles. There is little doubt that with suitable training, these same people could maintain and service fairly complex solar technologies such as Stirling engine electric generators and electrolysis units. Photovoltaic elements would require even less sophistication for their use and maintenence. As the systems grew along with a village (if growth occurs and if literacy and wealth increase), the necessary human organizations could correspondingly grow in size, diversity, and capabilities. What is important about many of the solar options is not that they will be cheap (they won't be) or primitive (they will often require technological elegance in their design and construction), but that they can break the bind that advanced energy technologies can now be widely used only where there is already a complex and sophisticated technical and managerial infrastructure in place. However, the introduction and diffusion of such technologies on a useful scale throughout the developing world will require a sensitivity to cultural factors [57, 58] that has rarely characterized attempts of the industrialized nations to provide technical assistance to these regions.

Potentially of great importance in the developing world would be a solar cooking system in which solar generated heat could be stored in sealed, insulated, and portable units to permit cooking in the evening and indoors (lack of these possibilities doomed previous attempts at introducing solar cookers in developing regions). Why? Because there is now a tragic firewood crisis [21, 45] pervading much of the developing world. Not only are the costs (in labor, money, and suffering) great, but the extraordinary scale of deforestation is resulting in an irreversible loss of valuable topsoil through erosion. It is ironic that a problem of such massive dimensions is being addressed neither by the developing nations, who have not seemed able to effectively apply science to solving such problems [70] nor by the industrialized nations, who have yet to establish in partnership with the developing countries the energy analog of the international agricultural research centers.

A global solar-energy system would have important potential benefits and liabilities for mankind. The system itself would be structurally resilient to a variety of natural and sociopolitical upheavals. The enormous geographic and geopolitical diversity of similarly sunny locations would permit global dispersion of the production capacity, decreasing the possibility of embargo by any one bloc of nations. Since the resource is nondepletable, stopping operation of the conversion facilities would result in loss of revenue (but not in continued amortization costs). The economic incentives associated with keeping oil and gas in the ground won't exist. This will be especially true for electricity production, where real bulk storage is not yet possible. (However, an exception could arise from the possibility for pumping hydrogen into local storage fields rather than shipping it.) In addition, user nations such as Japan and most of Europe could develop several years of strategic stockpiles (underground hydrogen) over a period of several decades, permitting more flexibility in responding to energy production shortages than is now possible.

Large geopolitical disparities in distribution of the remaining fossil resources (especially coal), potential hydropower, and reserves of uranium could lead to increasing international conflict as the stress between energy demand and availability grows. While solar technologies can provide no immediate relief, within a half century they could begin to provide a much more equitable distribution of needed energy, especially since the distribution of sunshine is so much more uniform than for these other resources. Also, the possibility for facilitating the rise of a new kind of rural society in a manner that seems impossible with nuclear sources is an exciting prospect.

The construction of such a system and its maintenance and operation would be the largest and most daring activity of mankind, and would not be without considerable difficulties—technical, economic, cultural, and environmental. But in terms of the scale of energy production that will ultimately be required even in the most modest growth scenarios, we must be willing to consider this route since we have only two options that we can more or less count on—the fast breeder reactor and the sun.

### Technical and Economic Basis

The development of most potentially important solar technologies is just beginning; present activities are emphasizing "hard," complex, and perhaps inelegant technologies because they are closest to our other industrial and engineering capabilities. However, progress is rapid and basic research, though still inadequately supported, is opening entire new possibilities, particularly in solid-state and photobiochemical conversion processes. The purpose of the following section is an attempt to establish the plausibility of solar-derived energy production in the range of 10–100 TW(th), not to prove its inevitability.

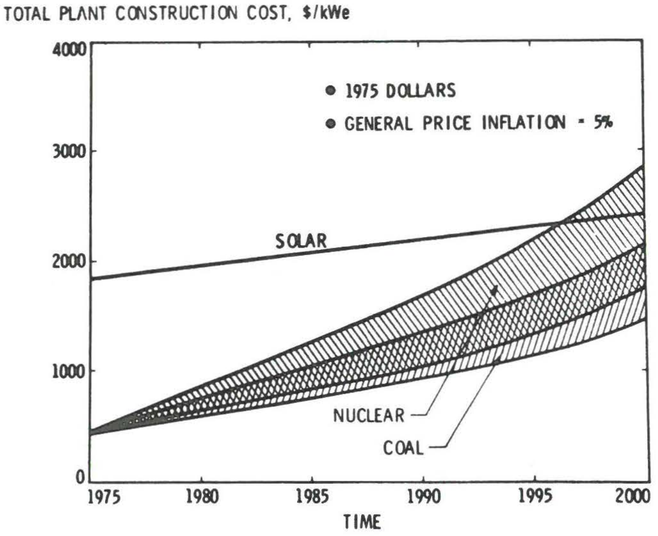
Economic judgements are difficult to make since it may take nearly a century for some mix of solar technologies to make a substantial fractional impact on energy use. To compare an expensive but emerging technology with a cheap and disappearing one (oil and gas) is inappropriate; the economics of solar technologies should be compared with those of the other energy sources that will also be available on a large scale during the same period—fusion and the fast-breeder reactor. Uncertainties in the technical and economic characteristics of these, plus the possible societal reactions, make it impossible to identify any one option as the preferred path. In fact, a diversity of options constitutes a vital insurance policy against future uncertainties. Caputo and Truscello [13] have shown that a modest difference in effective discount rates (Table 8) in favor of solar technologies would result in solar thermal electricity and the fast breeder reactor having essentially

**TABLE 8**

**Escalation Rates Used in Capital Cost Projections (%)**

| | 5% General price inflation assumed | | |
|---|---|---|---|
| | 1975–1980 | 1980–1990 | 1990–2000 |
| Upper limit—broad but decreasing social resistance | | | |
| Nuclear | 17 | 13 | 10.75 |
| Coal | 15 | 12 | 10.0 |
| Lower limit—long-term projected rates adopted immediately | | | |
| Nuclear | 10.75 | 10.75 | 10.75 |
| Coal | 10.0 | 10.0 | 10.0 |
| Solar—assumed to be socially acceptable | | | |
| | 6.2 | 6.2 | 6.2 |

*Source:* Caputo [13].




Courtesy of IECEC, U.S.A.

**Fig. 9. Projections of capital costs for solar, nuclear, and coal power plants [13].**

comparable costs (Fig. 9) by the year 2000. Again, this cannot be proven, but it again demonstrates the difficulties in attempting to identify an optimal energy system path into the future, *even* if direct costs were the only criterion.

THE SOLAR RESOURCE

Sunlight appears directly as radiant energy (both focusable and diffuse) and indirectly as wind, waves, ocean currents, thermal gradients in the tropical oceans, and the hydrological cycle. The high thermodynamic quality of direct radiation (Fig. 10), even after

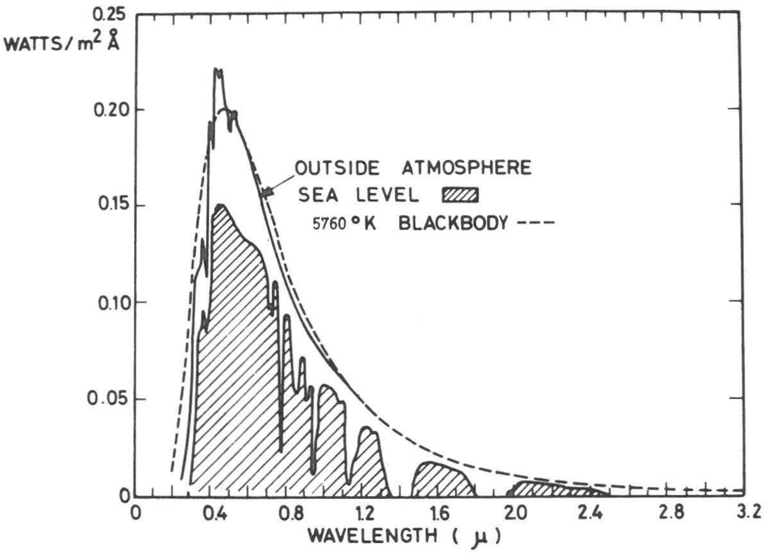



**Fig. 10. Spectral distribution of solar radiation in space and at sea level.**

passing through the atmosphere, permits the generation of heat at temperatures over the entire range required by industrial society (Fig. 11).

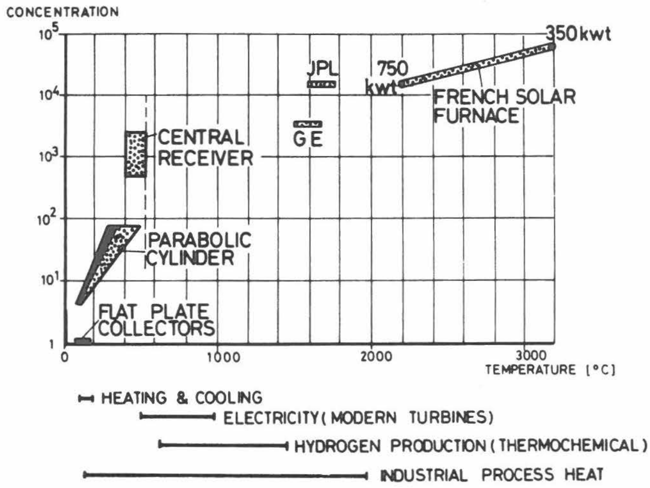



**Fig. 11. Temperature/concentration regimes for solar/thermal devices.**

Solar radiation is not strictly an energy resource, to be mined like fossil fuels or uranium, but is a power resource; it must be used when available (Table 9). It is incident at the top of the atmosphere at 1.4 kW/m² and rarely exceeds 1 kW/m² at the surface of the earth. Availability varies substantially from one place to another, with daily and seasonal variations superimposed on the weather. Radiant energy received at the ground averages (24 hr) 80–250 W/m², characteristic of Northern European and sunny, arid regions respectively. At normal incidence, the average direct beam or focusable radiation is as high as

**TABLE 9**

**Characteristics of Solar Radiation as an Energy Resource**

| | |
|---|---|
| The solar constant | 1353 W/m² |
| Effective radiation temperature of the sun | 5760 K |
| Maximum direct beam irradiation at sea level | ~1000 W/m² |

| Region, irradiance | | kWh/m²–day | W/m² (average) |
|---|---|---|---|
| Tropics, deserts | (Annual average horizontal) | 5–6 | 210–250 |
| Temperate zones | | 3–5 | 130–210 |
| Less sunny regions (e.g. Northern Europe) | | 2–3 | 80–130 |
| Average annual direct beam irradiance in sunny regions | (Annual average horizontal) | 7–8 | 290–330 |
| Monthly average direct beam irradiance in sunny, arid regions | | 5–10 | 210–420 |

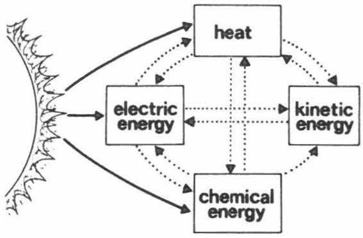



**Fig. 12. Pathways for direct conversion of solar energy.**

330 W/m$^2$ (continuous averaged power) in clear sky environments such as deserts, but falls to little more than 100 W/m$^2$ in much of central and northern Europe, where there is almost no direct radiation for many months in the winter. This direct beam radiation is central to the global scenarios presented here.

A SYSTEMS VIEW

Practical use of sunlight requires integrated energy systems incorporating energy conversion, storage, and transport [73]. There are two general possibilities—those that convert radiant solar energy directly and those that convert the various indirect manifestations of sunlight.

With wind, waves, and other indirect forms, the initial conversion stage will produce mechanical energy, which can be used to produce electricity, compressed and liquid air, and fuels. For direct conversion systems, the possibilities are even richer. A useful taxonomy of thermodynamic possibilities, based on the possible sequences of energy conversion contained in Fig. 12, is shown in Fig. 13, serving to distinguish the various possibilities.

In some cases, systems may be small and simple, such as a solar water heater which combines a solar collector with plumbing (energy transport), a storage tank, suitable pumps and controls, and an auxiliary heater. Increasing in size and complexity would be solar heating serving a large apartment complex, a 100-MW(e) solar power plant incorporating thermal storage, and an integrated electric utility system incorporating a mix of generation, storage, and transmission elements, including solar buildings and solar electric plants, and, a system of solar thermochemical hydrogen plants (Fig. 8) coupled globally to demand centers via pipeline and cryogenic tanker, with underground storage in suitable geological formations. Any evaluation of solar technologies must be in terms of the total required systems, not just the conversion elements.

THERMAL ENERGY

In the industrialized nations, 35–50% of all primary energy is used for low-grade end uses ($<$100°C), primarily space heating. Another 20–25% is for industrial process heat above 100°C [4]. In principle, some fraction of this market could be served by solar thermal technologies. The technology for solar water and space heating is now well established commercially in many countries [18]. Dozens of prototypes and thousands of commercial solar homes have been built or are under construction in the United States, and very rapid expansion of the industry is expected.

And yet the ultimate potential displacement of other forms of energy by solar thermal techniques is small. In new buildings, energy conserving and passive solar architecture

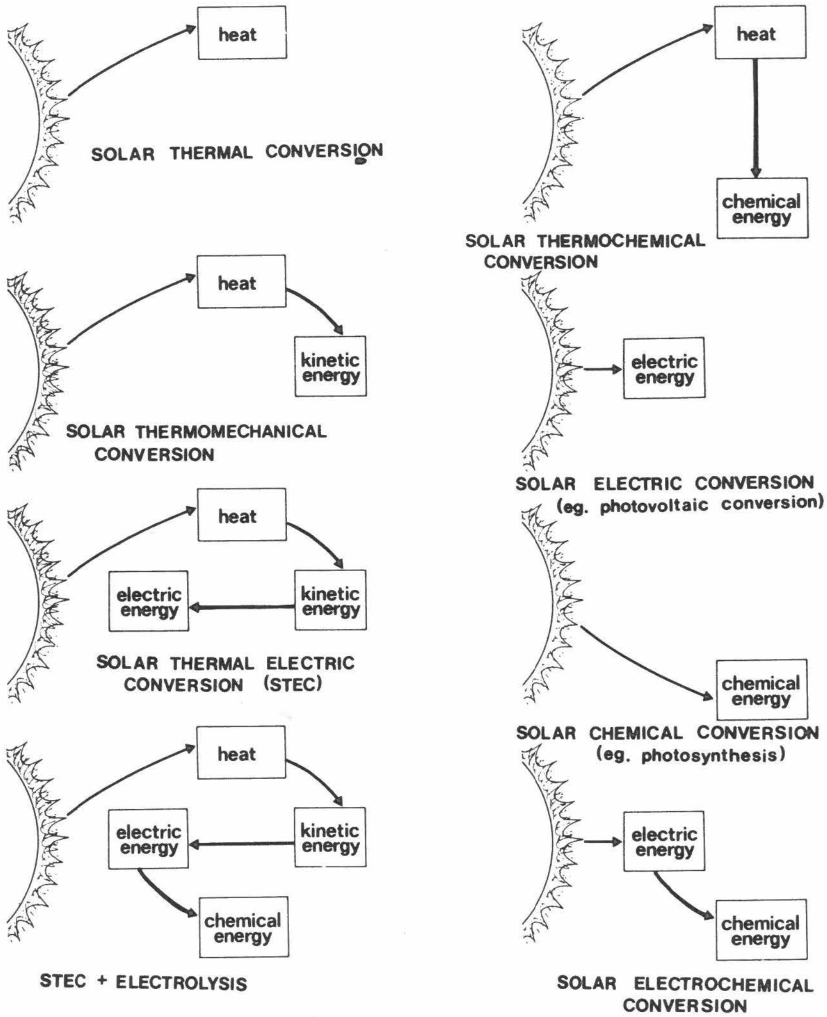



**Fig. 13. Some thermodynamic classes of solar energy conversion.**

[52] and energy-efficient heating and cooling systems are far more cost effective, often by a factor of 5–10 [27] than active solar heating and cooling. These measures can cut present residential energy demand (Table 10) by substantial factors (Table 11), almost to the point where a modest amount of solar heating can provide the entire residual demand, even in cold climates like Denmark. Even retrofitting of residential buildings is substantially cheaper (Table 12) than providing additional energy, whether by solar [61] or conventional means, and, unlike direct solar heating, does not aggravate the peak load problems of electric or gas utilities. Solar heating is essentially a mature commercial activity and seems unlikely to experience much cost reduction in the future. A possible exception, yet undemonstrated, might be the integration of solar energy systems elements into the systems building process [60] which has succeeded in a few European countries but is

**TABLE 10**

**Residential Energy Use in Europe and the United States[a]**

| | Dwelling type[b] | Thermal loss kW(th)-hr/year | System efficiency[c] | Fuel demand kW(th)-hr/year |
|---|---|---|---|---|
| United States | SFD | 25,600 | 0.63 | 40,000 |
| | MFD | 16,900 | 0.63 | 26,800 |
| West Germany | SFD | 26,800 | 0.65 | 41,200 |
| | MFD | 15,400 | 0.65 | 23,700 |
| Netherlands | All | 15,000–20,000 | 0.55 | 27,000–36,000 |
| Denmark | SFD | 21,800 | 0.70 | 31,000 |
| | MFD | 13,600 | 0.75 | 18,100 |

[a] *Source:* WAES [71].
[b] *Note:* SFD = "single family dwelling"; MFD = "multiple family dwelling."
[c] System efficiency is for fossil-fuel conversion in the home. Efficiency of electric heat is considered 1 at end use; overall efficiency is approximately 0.33.

unlikely to be an option in the United States for many decades [6]. Today there are few places where active solar heating is competitive; in Central Europe the effective cost of solar heating is between $5000 and $10,000 per average thermal kilowatt (Table 13).

Independent of economic considerations are logistic problems. In much of the industrialized world over half the space heating is in urban areas where there is insufficient roof area for solar heating. Assuming that 50% of the remaining market could be penetrated by solar techniques (unlikely on economic grounds), and observing that the economically optimum solar heating systems supply 50–70% of total annual heating demand (itself only 30% or so of total energy demand), the ultimate displacement of other primary energy

**TABLE 11**

**Annual Demand for Heat and Fuel for Various Houses[a]**

| Building type | Thermal demand[b] | Fuel demand[b] |
|---|---|---|
| Average U.S. house | 28,600 | 44,000 |
| New house with present insulation practice | 12,600–18,900 | 20,000–30,000 |
| Easily achievable with cost-effective insulation practice | 8,820–12,600 | 14,000–20,000 |
| Achievable with strong conservation measures | 4,400–6,300 | 7,000–10,000 |
| Addition of solar space heat | 0–3,000 | 0–5,000 |
| "Zero-energy house" in Denmark | 0 | 0 |

[a] *Source:* WAES [71].
[b] kW(th)–hr/year, system efficiency = 0.63 (fuel to useful heat).

**TABLE 12**

**Energy-Conservation Measures—Costs and Energy Savings in a Typical U.S. House[a]**

| Conservation measure | Energy/year [kW(th)–hr] | Cost of measure [$/kW(th)] | Cost to save energy [$/kW(th)–hr] | Cost to save energy [$/GJ] | Energy use as fraction of original |
|---|---|---|---|---|---|
| Initial insulation R7 in walls | 31,000 | — | — | — | 1.00 |
| Reduce inside temp. from 22°C to 21°C | 27,000 | 0 | 0 | 0 | 0.89 |
| Install storm glazing | 23,200 | 950 | 0.011 | 3.2 | 0.75 |
| Install R19 ceiling insulation | 19,400 | 921 | 0.011 | 3.1 | 0.63 |
| Night setback in thermostat to 16°C | 16,400 | 0 | 0 | 0 | 0.53 |

[a] 135-m² Single-family dwelling in New York State, 4800 degree days/year (heating):

| | |
|---|---|
| Total investment | $890.00 |
| Annual energy savings | 14,600 kW(th)–hr |
| Investment | $520/kW(th) at 100% load factor |
| Equivalent cost of | $0.006/kWh(th) = |
| Displaced energy | $7.30/bbl heating oil combusted at 70% efficiency |

forms by solar heating would be $(0.5) \times (0.50) \times (0.5-0.7) \times (0.3) = 3-4\%$. If energy conservation further decreases the total thermal energy demand of buildings by 50%, the potential is even smaller.

Similar constraints limit the possible use of high-temperature solar heat for industrial processes, although it is conceivable that new industries developed in sunny regions could explicitly use high-temperature solar heat, provided it can be competitive.

## SOLAR THERMAL HYDROGEN

In principle, hydrogen can be produced at potentially interesting costs from solar (and nuclear) generated high-temperature heat (600–2500°C), although a thermochemical hydrogen production process amenable to large-scale commercial use has yet to be developed. However, over 10,000 possible thermodynamic cycles have been identified, and the efficiency of conversion from heat to hydrogen will be in the range of 30–90% [28], depending in part on the temperature of the reaction (550–2000°C). Advanced high-temperature reactors produce heat at 1000°C; the reactor for the now abandoned U.S. nuclear rocket program operated at 2500°C. High-efficiency conversion of sunlight to heat can be achieved at even higher temperatures using the solar central receiver technology (described below) or solar furnace systems similar to that at Odeillo, France.

Farbman [23] has carried out an extensive study of one process that has already been demonstrated by Westinghouse at the laboratory scale. The system is a hybrid electrolytic-thermochemical process for decomposing water. It is driven by helium as a high-temperature thermal exchange fluid, which can be produced by a high-temperature reactor or by a high-temperature solar-thermal system. Projected efficiencies (heat to chemical energy in the form of hydrogen) are as high as 60%. Farbman estimates that a

**TABLE 13**

**Solar Space Heating: An Economic Example for Central Europe**

| | |
|---|---|
| Solar-system cost[a] ($/m² collector) | $250/m² |
| Average insolation[b] | 3–4 kWhr/m²–day |
| Annual net utilization[c] | 0.20–0.35 |
| Fraction total heat requirement supplied by solar[d] | 0.70–0.50 |
| $/kW(th)$_{average}$ | $4,300–$10,000 |
| m²/kW(th)$_{average}$ | 17–40 |
| Cost of solar heat at 10% fixed charge rate on solar equipment[e] | |
| $/kWhr(th) | 0.05–0.11 |
| $/kJ(th) | $14–$32 |
| Parity cost of heating oil combusted at 65% efficiency ($/bbl) | $55–$126 |
| Present cost of heating oil, including local taxes | ~$30/bbl |

[a] Total costs of solar-specific equipment expressed in $/m² of solar collector; $250/m² is at the low end of the spectrum of installed costs.

[b] Typical of all of Central Europe [kWhr(th) useful heat per incident kWhr of sunshine].

[c] Expected for range of climatic conditions in Central Europe; verified by many U.S. and European solar-heating experiments and simulation models.

[d] Higher percentages supplied by solar heat correspond to *lower* total-system heat-utilization factors.

[e] Actual fixed charge rates will be typically in the range of 10–20%; hence the solar heat costs derived here are conservatively low.

**TABLE 14**

**R & D Costs and Commercialization Dates for Advanced Power Plant Designs in the USA**

| System | Date commercial | R & D costs (billion $) |
|---|---|---|
| Fluidized bed (coal) | 1981 | 1.0 |
| Coal–gas combined cycle | 1984 | 1.5 |
| Liquid metal fast breeder | 1987 | 2.0 (FRG)<br>10.0 (USA) |
| High temperature gas cooled reactor | 1984 | 1.5 |
| Central receiver solar electric | 1990 | 1.0 |

**TABLE 15**

**Cost Estimates for Production of High Temperature Heat (>600°C) by Solar Central Receiver Systems**

| $/kW(th)[a] | Reference |
|---|---|
| 2050 | Jet propulsion laboratory (1975) |
| 1500 | McDonnell (1975) |
| 1840 | Martin (1975) |
| 1700 | Black & Veatch (1977) |
| 1170 | Smith (1976) |
| 1653 ± 333 | |

[a] Adjusted to 100% load factor.

commercial prototype pilot plant could be operational in less than a decade, with development costs below $100 million. By comparison (Table 14), development costs [14] for the high-temperature gas-cooled reactor, synthetic natural gas production, and the central receiver solar thermal electric power plant are all in the range of one billion dollars, with even higher development costs for the fast-breeder reactor.

Unfortunately, no country is *aggressively* pursuing the development of such processes, in spite of their potential significance. The research that has been carried out and present cost estimates for high-temperature solar thermal generation suggest that solar thermochemical hydrogen produced in sunny clear-sky regions could be produced at a cost in the range of $40 to $100 per barrel of oil equivalent (Tables 15 and 16). Although this may seem excessive, it is important to realize that the present prices (before taxes) of refined petroleum-based fuels such as gasoline are *already* on the order of $20 per barrel.

SYNTHETIC LIQUID FUELS

Gaseous fuels are not enough; high-quality liquid fuels will continue to be essential, especially for fueling vehicles and aircraft, and also are an alternative to the ocean-based transport of liquid hydrogen. Haefele [32] has proposed increasing by sixfold the efficiency with which the carbon atoms in fossil fuels (especially coal) are used by combining

**TABLE 16**

**A Rough Estimate—Economics of Solar Thermochemical Hydrogen Production**

| Subsystem | $/kW(th)[a] |
|---|---|
| Solar thermal | 1650 ± 300 |
| Thermal hydrogen | 600 ± 400 |
| TOTAL COSTS | 2250 ± 350 |

[a] At 100% effective load factor, FCR = 0.10 $2250 ± 350/kW($H_2$)→$44 ± 7/"bbl". Gasoline without taxes: $20 to $40/bbl.

coal and nuclear and/or solar-derived hydrogen to create methanol. An alternative process, which permits the production of methanol or similar high-quality carbonaceous fuels from hydrogen, is the catalytic recombination of hydrogen with carbon dioxide extracted directly from the atmosphere or oceans. A recent study [64] indicates that such a process operating at high efficiency is technically feasible and may be economically attractive.

SOLAR THERMAL ELECTRICITY

Direct-beam sunlight can be converted to electricity at high efficiency (17–25%) using a thermal/mechanical cycle. The purely technical feasibility of such conversion (although at lower efficiencies) has been established ever since the invention of the practical electrical generator, which could have been coupled with a solar-driven heat engine almost a century ago. However, the development of efficient and reliable solar electric power plants suitable for integration with modern electric grids was initiated only 5 years ago. Already a variety of small systems in the 1–100-kW range are commercially available. Technologies that will lead to solar power plants as large as several hundred MW(e) are already well under development in the United States, Europe, and Japan. A 400-kW(th) prototype is in operation in Georgia (U.S.A.), and a 5-MW(th) solar test facility is nearing completion in New Mexico. Within the coming decade, perhaps half a dozen or more large-scale prototype systems will be constructed setting the stage for possible commercialization in the 1990s (Table 17).

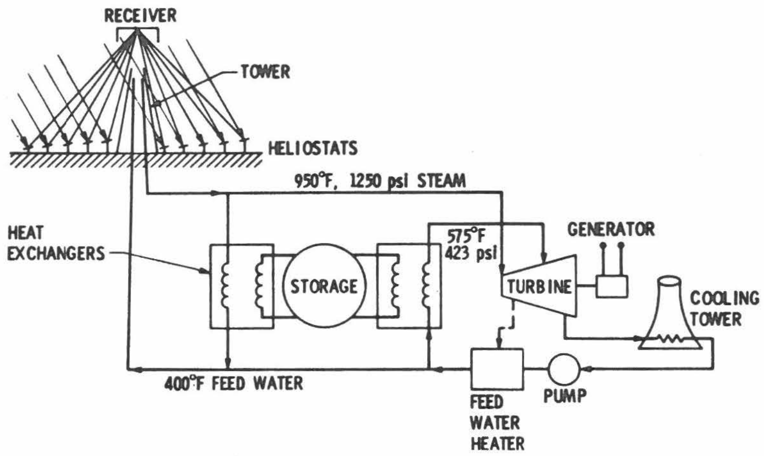
**TABLE 17**

**Constructed, Planned, or Contemplated Central Receiver and Distributed Solar Thermal Electric Facilities**

| Facility | Location | Capacity | Completion | Sponsors[b] |
|---|---|---|---|---|
| Solar furnace | Odeillo, France | 1.0 MW(th) | 1969 | CNRS |
| Solar thermal test facility | Albuquerque, New Mexico (U.S.A.) | 5.0 MW(th) | 1978 | ERDA |
| Central receiver (steam cycle) | Genoa, Italy | 0.1 MW(e) | mid-1960s | Prof. Francia |
| Solar thermal central receiver test facility | Georgia Institute of Technology, Atlanta, Georgia (U.S.A.) | 0.4 MW(th) | 1977 | ERDA |
| Central receiver, steam cycle | Southern France | 2.0 MW(e)[a] | 1980 | CNRS |
| Central receiver, steam cycle | Barstow, California (U.S.A.) | 10.0 MW(e) | 1981[a] | ERDA, SCE, LADWP |
| Distributed system, steam cycle | (to be determined) | 10.0 MW(e) | 1982[a] | ERDA |
| Central receiver, steam cycle | Southwest U.S.A. | 100.0 MW(e) | 1985[a] | ERDA |
| Distributed system, steam cycle | Southwest U.S.A. | 100.0 MW(e) | 1985[a] | ERDA |
| Central receiver gas turbine hybrid with fossil fuel backup | Southwest U.S.A. | 2.0 MW(e) | 1981[a] | EPRI |
| Central receiver | Spain | 1.0 MW(e) | 1980 | European Community |

[a] Approximate.

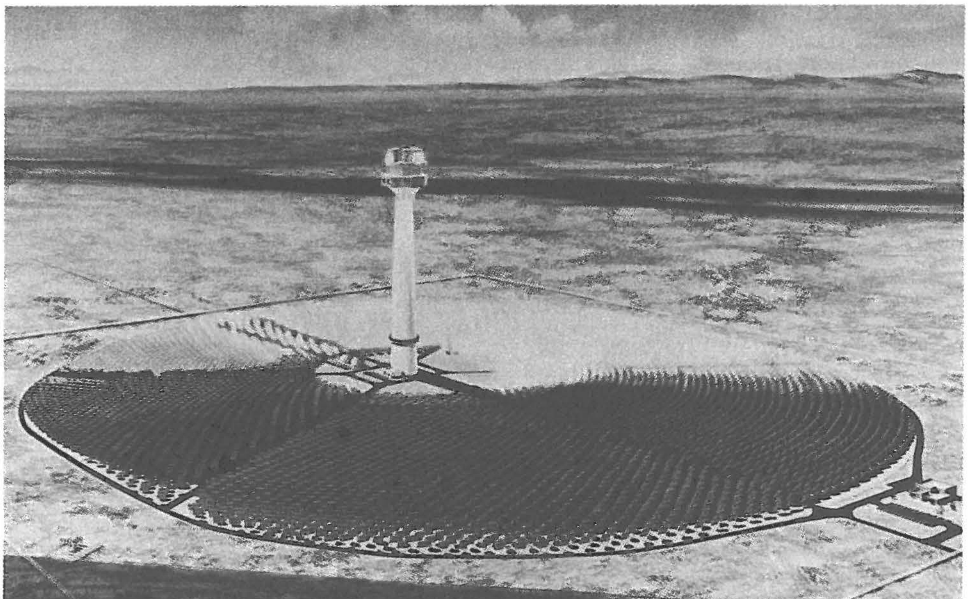
[b] CNRS = Centre National de la Recherche Scientifique (France); ERDA = Energy Research and Development Administration (U.S.A.); SCE = Southern California Edison Company (U.S.A.); LADWP = Los Angeles Department of Water and Power (U.S.A.); EPRI = Electric Power Research Institute (U.S.A.).




Courtesy of NASA Jet Propulsion Lab, C.I.T., Pasadena, Calif.

**Fig. 14. Central receiver solar thermal electric power plant [13].**

No approach has emerged as clearly superior, but present emphasis for large plants is on the "central receiver" system (Fig. 14). In this design (Fig. 15), direct sunlight is reflected from a field of movable mirrors ("heliostats") and focused on an absorber mounted atop a high tower, producing superheated steam or hot gases to drive turbines. Thermal storage is used to buffer the turbines against rapid changes in sunlight, and



Courtesy EPRI, Palo Alto, Calif.

**Fig. 15. 60 MW(e) open cycle gas turbine solar electric plant.**

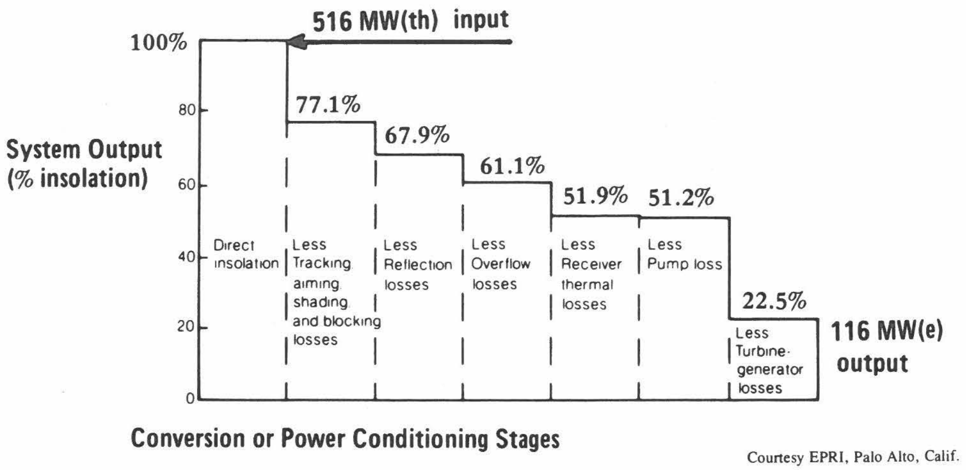



**Fig. 16. Calculated performance of a closed Brayton cycle (helium) solar thermal electric power plant (calculated at summer solstice for Inyokern, Calif., U.S.A.).**

additional thermal, electrical, or mechanical storage or hybrid operation (combustion of fossil fuels) can provide additional reliability and extended operation, even into the base load regime. A 100-MW(e) plant in a sunny region would operate six to eight hours per day at full capacity and would require approximately 15,000 heliostats, each with a reflecting surface area of 35 $m^2$ and a central tower approximately 260 m in height. To avoid shading and blocking of adjacent heliostats, the 0.5 $km^2$ of total reflecting surface plus the tower and associated facilities would occupy a region of approximately 1.2 $km^2$. Net conversion efficiency for these plants will be in the range of 17–25% (Fig. 16).

First-generation designs using steam turbines and second-generation systems using high-temperature gas turbines are under development. Open-cycle gas turbines have the advantage that no cooling water is required, which is a crucial consideration for most arid regions of the world.

Although an extensive engineering effort is necessary for the evolution to commercial solar plants, virtually every component is commercially available or can be developed with well-understood applications of present technology. Engineering problems as-

**TABLE 18**

**STEC Total Cost Estimates**

| \$/kW(e)[a] | Reference |
|---|---|
| 2700 | JPL (1975) |
| 2100 | McDonnell (1975) |
| 2700 | Martin (1975) |
| 2260 | Black & Veatch (1975) |
| 1610 | O. Smith (1976) |
| 2274 ± 456 | |

[a] Load factor = 0.5; 1977 dollars; direct costs × 1.5 = total costs, central receiver system.

**TABLE 19**

**Estimated Cost Components for Recent Central Receiver STEC Power-Plant Designs**

| Cost component[a] | JPL (1) | McD (2) | Martin (3) | B & V/ EPRI (4) | B & V/ EPRI (5) | SMITH (6) | CSU (7) | ANSALDO MBB (8) | JPL (9) |
|---|---|---|---|---|---|---|---|---|---|
| Land and site preparation | 10 | | 115 | 27 | 10 | 11 | 33 | — | 6.5 |
| Structures and facilities | — | 32 | | 110 | — | — | — | 3300 | — |
| Heliostats and collectors | 935 | 678 | 760 | 1933 | 620 | 616 | 185 | | 1458 |
| Absorber/receiver | 230 | 143 | 180 | 658 | 348 | 99 | 23 | 560 | |
| Boiler plant | | | 182 | | N/A | | | | 250 |
| Turbine plant | | 230 | 83 | 145 | 262 | 200 | 74 | 1000 | |
| Electric plant | 250 | | | | | | | 600 | |
| Misc. plant equipment | | 5 | | 98 | 52 | 10 | 5 | | 268 |
| Condensor and cooling | | | 61 | 98 | N/A | — | 23 | | |
| Storage | 122 | 122 | 169 | 127 | 7 | 60 | 170 | (none) | 122 |
| Direct costs | 1547 | 1210 | 1550 | 3196 | 1299 | 996 | 513 | 5460 | 2104 |
| Indirect costs (50%) | 773 | 605 | 775 | 1598 | 650 | 498 | 257 | 2730 | 1052 |
| IDC of originator | (551) | — | — | (700) | (364) | (326) | (60) | (300) | (760) |
| Total direct and indirect costs $/KW(e) | 2320 | 1815 | 2325 | 4794 | 1950 | 1494 | 770 | 8190 | 3156 |
| (year estimated) | (75) | (75) | (75) | (75) | (75) | (76) | (73) | (76) | (75) |
| Total direct and indirect costs updated to 1977 | 2700 | 2100 | 2700 | 5560 | 2260 | 1610 | 1050 | 8850 | 3550 |
| Plant rating in MW(e) | 100 | 100 | 100 | 50 | 50 | 100 | 161 | 1.0 | 100 |
| Cycle | steam | steam | steam | steam | open brayton | steam | steam | steam | steam |
| Cooling | dry | wet | dry | dry | direct | pond | wet | wet or dry | wet |
| Storage (hr) | 4.2 | 4 | — | 6 | weeks | 6 | 2 | 0 | 4.2 |

[a] All costs in $/kW(e) rated.

sociated with high-intensity solar-radiation absorbers operating under rapidly changing high-temperature conditions are being solved, and for the heliostats and thermal storage elements, many designs are being explored in parallel to determine the most economic approaches.

Expected commercial costs (1977$) for the large systems (Tables 18 and 19), based on many detailed engineering studies, are $2440 ± $300 per kW(e) at 0.5 load factor, corresponding to a busbar electricity cost of $0.08 per kW(e)-hr (at a fixed charge rate of 0.15). While even the best of engineering cost estimates tend to underestimate actual production costs, these suggest that the possibilities are good that STEC power plants will be competitive, especially in the intermediate load regime, with alternatives by the end of this century. This may be especially important if social and environmental factors con-

TABLE 20

**Production and Transmission of Solar Thermal Electricity**

| Cost component | Cost (mills/kW(e)–h) |
|---|---|
| ±800 kV DC high voltage transmission | |
| 3000 km | 5 |
| 5500 km | 7 |
| 8000 km | 10 |
| STEC electricity production [$2000–$3000/kW(e), 0.5 load factor, 0.15 FCR] | 70–100 (deserts)<br>200–300 (Central Europe |

tinue to drive up the price of fission and coal systems faster than the increase in costs for otherwise similar technologies and industrial processes.

As in the case of solar thermochemical hydrogen production and transport, the costs of production of electricity from STEC plants in *optimum arid sunny regions* exceeds long distance HVDC transport costs by a factor of 10 (Table 20).

PHOTOVOLTAICS

High-efficiency direct conversion of sunlight to electricity by solid-state means is potentially one of the most important solar technologies, both for developing and industrialized countries. With suitably prepared thin layers of silicon or thin films (Fig. 17) of other semiconductor materials, conversion efficiencies of 10% to over 20% have been achieved. With concentrating optics the size of the photovoltaic device is substantially reduced for a specific output, and even higher efficiencies can be achieved (Table 21). Photovoltaic units have no moving parts and require virtually no advanced skills in their maintenance (cleaning); they are noiseless and pollution-free, which means they can be used anywhere, and they are equally responsive to direct and diffuse radiation. There are no fundamental materials limitations on silicon, and with the use of high optical concentration, even known limited resources of Ga correspond to 100 TW(th). The arrays can be used on virtually any scale, with modules of a few watts powering educational television sets in remote rural locations to large, integrated complexes of hundreds or even thousands of megawatts. The modularity of the arrays and of accompanying power conditioning and storage units permits the possibility of "microgrids" at the village and town scale, with the eventual possibility of growth and interlinking to form minigrids and larger systems. In LDCs this modularity permits the addition of generating capacity in a way that could match growth in local capabilities, resources and wealth, something not achievable in rural areas with large-scale nuclear and fossil-fuel plants. Perhaps most significant, the lifetime of certain photovoltaic elements, such as silicon, is measured in *millenia,* not decades. New techniques to assure effective sealing, such as integration of the silicon with a glass cover (already experimentally demonstrated) and protection against corrosion of metallic conductors must be commercially developed. Large-scale production may be similar to the present production of very complex multilayer planar structures—color film. As formidable as this seems, can anyone who has witnessed the development of instant color film and instant color motion picture film really question the possibility to develop a mass-produced, economically interesting photovoltaic array? With such a development

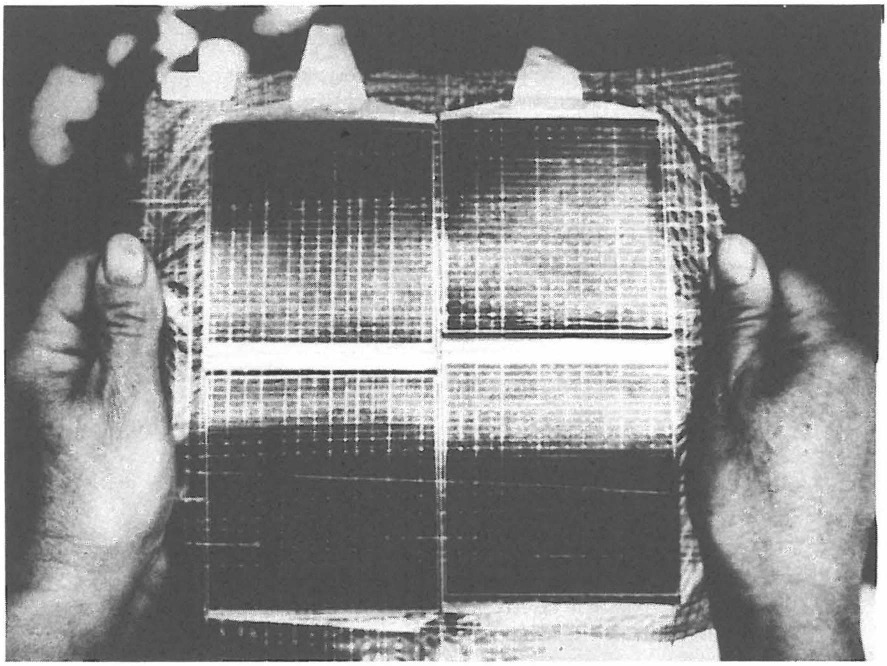


Photo: J. Weingart.

**Fig. 17. Prototype thin film cadmium sulfide solar cell unit.**

would come the extraordinary possibility of giving to tens and possibly hundreds of human generations a true energy dowry. Our present Western economic system, which discounts the value of most technology to negligible amounts in a matter of decades provides no useful way for us to evaluate such an unprecedented technological lifetime for an energy supply system.

The most commercially advanced photovoltaic unit is the silicon solar cell, originally developed for spacecraft applications. Spacecraft arrays cost roughly $50,000 per peak kW(e). However, present costs of the terrestrial versions are already down to roughly $5,000 per peak kW(e) (under maximum sunlight illumination), corresponding to $15,000–$25,000 per average kW(e). Further reduction to $2,000 per peak kW(e) is expected within a few years, and the U.S. Dept. of Energy is aiming for $500 per peak

**TABLE 21**

**Characteristics of Photovoltaic Conversion Units Under Intense Concentrated Illumination**

| Material | Concentration | Efficiency | Temp. (°C) | Cooling | Reference |
|---|---|---|---|---|---|
| GaAs/GaAlAs | 500–1800 | 0.20 | <50 | Forced | Varian (1975) |
| Silicon | 1500 | 0.25 | 15 | Forced | Chappel & White (1977) |
| Silicon | 50 | 0.10 | 100 | Passive | Sandia (1976) |
| Silicon | 300– 500 | 0.10 | <50 | Passive | RCA (1976) |
| Silicon | 300–1500 | 0.20 | 20 | Forced | Schwartz (1976) |

**TABLE 22**

**Estimated Photovoltaic Array Subsystem Costs**

| Optical concentration | Array conversion efficiency | Tracking capability | $/m² array | $/m² cell | $/m² structure | $/kW(e)$_{average}$ |
|---|---|---|---|---|---|---|
| 1 | 0.12 | fixed, tilted | 50 | | 15 | 2200 |
| 1 | 0.12 | E-W tracking | 50 | | 25 | 2000 |
| 1 | 0.05 | fixed, tilted | 20 | | 15 | 2800 |
| 1 | 0.12 | fixed, tilted | 100 | | 15 | 3800 |
| 1 | 0.12 | E-W tracking | 200 | | 25 | 6000 |
| 1.5- 3 | 0.12 | CPC fixed | | 50 | 30 | 1700 |
| 10 - 20 | 0.12 | 2-axis tracking | | 100 | 50 | 1500 |
| 20 - 50 | 0.12 | 2-axis tracking | | 500 | 50 | 1800 |
| 30 - 60 | 0.12 | 2-axis tracking | | 2,000 | 150 | 5300 |
| 40 - 90 | 0.12 | 2-axis tracking | | 2,000 | 75 | 3000 |
| 60 -150 | 0.15 | 2-axis tracking | | 2,000 | 50 | 1600 |
| 300 -600 | 0.18 | 2-axis tracking | | 20,000 | 75 | 2000 |

*Note:* $2,000/kW(e)$_{average}$ at 0.10 fixed charge rate; $0.023/kWh(e).
[a] Sandia (1976). System assumed to operate in Albuquerque, New Mexico (U.S.A.).
[b] "CPC" = Compound parabolic concentrator. (Winston, 1976).
[c] U.S. Dollars, late 1975.

kW(e) by 1985. The present emphasis in the U.S. photovoltaics program is on the achievement of continued reduction of costs of silicon photovoltaics through industrial development stimulated by large government purchases of solar cell modules. These cost breakthroughs (projected in part on the basis of an erroneous comparison of the per unit transistor function cost trends within the semiconductor industry) may not be attainable, and a much more aggressive parallel research and development program on other approaches is called for.

One important breakthrough in industrial production of single-crystal silicon suitable for high-efficiency solar cells is the process for continuous growth of single crystal ribbons of silicon by the Mobil-Tyco Solar Energy Corporation. The eventual price of complete photovoltaic arrays is estimated to lie in the range of $400–$600 per peak kW(e) or $1,200–$1,800 per average kW(e), depending on local sunlight conditions (Table 22). Full system costs, including storage, transmission and power conditioning, labor, and indirect costs suggest photovoltaic power plants would be roughly $2,000–$6,000 per average kilowatt. We can also imagine the production of completely integrated, thin sheets of weather-proof high-efficiency thin-film conversion elements, which could be stretched on light-weight, but highly rigid space frames; here perhaps the possibility is for costs below $1,000 per average kW(e).

Recent advances in electrochemistry [46] have indicated the possibility of a high-efficiency photoelectrochemical cell as an alternative to the photovoltaic cell. These new devices, in the experimental stage, make possible *in situ* energy storage as well as conversion and can, in principle, resolve the very thorny problem that electricity storage will be required in association with photovoltaic conversion for any commercial electric applications.

**TABLE 23**

**Biomass Energy Yields of Selected Plant Species**

| Species | t/ha-yr | $10^8$kJ/ha-yr | W(th)/m$^2$ | Conversion efficiency (%)[a] |
|---|---|---|---|---|
| Corn | 20 | 3.5 | 1.1 | 0.5 |
| Sorghum | 70 | 12.2 | 3.9 | 1.9 |
| Water Hyacinth | 36 | 6.3 | 2.0 | 1.0 |
| Sugar cane | 30–110 | 5–20 | 1.6–6.4 | 0.8–3.5 |
| Suban grass | 36 | 6.3 | 2.0 | 1.0 |
| Hybrid Poplar | 18 | 3.1 | 1.0 | 0.5 |
| American Sycamore | 9 | 1.6 | 0.5 | 0.25 |
| Eucalyptus | 20–50 | 3.5–8.7 | 1.1–2.8 | 0.5–1.3 |
| Fresh-water Algae | 90 | 16 | 5.1 | 2.5 |

*Source:* Ahlich and Hinman, [2].
[a] Average insolation of 5 kWh/m$^2$–day = 210 W/m$^2$.

BIOCONVERSION

Poole [55] has suggested that possibly as much as 10 TW(th) could be produced from bioconversion processes for human energy needs. Sweden is considering converting a fraction of its forest products industry to an energy industry, with expected favorable changes in balance of payments [42], and Brazil has embarked on an ambitious program to produce ethanol from sugarcane to displace gasoline for transportation.

Photosynthetically produced sugar and starch and hydrocarbons [11, 12] can be converted to useful, high-quality fuels by fermentation and other processes. However, the net productivity of the most efficient plants is low, with a maximum of 2–3% for such species as water hyacintn, sugarcane, and fresh-water algaes (Table 23). Subsequent conversion to useful high-quality fuels further lowers overall efficiency to 1–2%. Substantial land is required if photosynthetically derived fuels are to be used on a large scale. At least 5 million square kilometers would be needed for a sustained 20 TW(th) world, the lowest of the long-term energy-demand scenarios considered here. By comparison, 14 million square kilometers are now under cultivation for food production.

For many regions of the world biomass production has the advantage that it is a well-understood process and that fermentation, digestion, and other conversion processes can be extended to high-efficiency plant matter without major technological breakthroughs. In addition, genetic engineering and research on the photosynthetic process may lead to plants especially developed for energy production. Since little research has been directed at the development of biological systems optimized for this purpose, we can speculate that strong research in this field could have important payoffs.

OCEAN THERMAL ELECTRIC CONVERSION (OTEC)

The energy contained in the thermal gradients of the tropical oceans (20°C over several hundred meters depth) could power low-temperature turbines to produce electricity, fuels, and liquid air on a very large scale. It is estimated that as much as 150 TW(th) could be produced with OTEC plants distributed over the entire oceans between ± 20° of latitude. A "practical" upper limit of 1–10 TW(th) has been assumed here, with environmental and climatic impacts assumed to be limiting factors. However, this is only a rough

**TABLE 24**

**Estimated Capital Costs for OTEC Plants**

| | Costs in \$/kW(e) | | |
|---|---|---|---|
| Designer | Direct | Indirect[a] | Total |
| Carnegie Mellon University | 2580 | 1290 | 3870 |
| University of Massachusetts | 2030 | 1020 | 3050 |
| Solar Sea Power, Inc. | 1800 | 900 | 2700 |
| TRW Systems, Inc. | 2450 | 1230 | 3680 |
| Lockheed Missiles & Space | 3057 | 1530 | 4590 |
| Black & Veatch | 2560 | 1280 | 3840 |

Average = \$3622 ± \$670 (1 S.D.).
[a] 50% of direct.

guess, and the ultimate limits might be much higher; much more has to be known about the potential impacts of OTEC systems before a better bound can be estimated. For the moment, technical uncertainties, high projected energy production and transport costs as well as potentially problematic environmental effects raise serious questions about this option. Minimizing biofouling and overcoming the high costs of heat exchangers are significant remaining engineering challenges.

Engineering studies by TRW [66] and Lockheed [41], among others, indicate the technical feasibility of developing such plants. The average cost for six different engineering concepts is \$3,600 ± \$700 for the best locations (Table 24), and could easily be 50% higher for many other locations. Few suitable locations are within present practical undersea high-voltage electric transmission distances, and a liquid fuel transportable by ship must be developed if this option is to be strategically important. If this fuel were to be hydrogen, produced by electrolysis, the total costs of production, liquefaction, and cryotanker transport could be over one hundred dollars per "barrel" equivalent of oil (Table 25).

**TABLE 25**

**Costs for Production and Liquefaction of Hydrogen OTEC Plants Using Electrolysis**

| Process | $H_2$ Costs (\$/bbl) |
|---|---|
| Electricity from OTEC (1) | 45–180 |
| & $H_2$ by electrolysis (2) | 12 |
| Liquefaction of $H_2$ | 25–75 |
| 6000 km cryotanker transport | 3–8 |
| Landed cost | 85–275 |

(1) \$2000/kW(e), 0.9 LF, 0.10 FCR = \$45/bbl
\$3600/kW(e), 0.8 LF, 0.15 FCR = \$180/bbl
(2) Electrolysis equipment at \$400/kW($H_2$), 0.15 FCR = \$12/bbl, remainder of costs from OTEC electricity

**TABLE 26**

**Global Land Use and Solar Energy Conversion Area Requirements**

| Present use | Region | Area ($10^6 km^2$) | % Total |
|---|---|---|---|
| Full use | Human settlements | 0.4 | 0.3 |
| Full use | Arable land | 13.0 | 8.8 |
| Partial use | Pastures | 21.3 | 14.3 |
| Partial use | Forests | 35.3 | 23.8 |
| Usable | (but not practical) | 3.9 | 2.6 |
| Unused | Wastelands, deserts, mountains | 62.1 | 41.8 |
| | Uninhabited islands & polar regions | 12.5 | 8.4 |
| Total | Global land mass | 148.5 | 100.0 |
| Solar conversion | 8 TW | 0.15 | 0.1 |
| (Net production rate | 50 TW | 1.0 | 0.7 |
| = 50 W(th)/$m^2$ land) | 400 TW | 8.0 | 5.4 |

*Source:* Doxiadis and Papaionnou [20].

## Constraints

The global scenario sketched in this paper is subject to important constraints. Capital requirements may well exceed those for an equivalent scale of energy production based on the breeder, although the economic uncertainties associated with presently external considerations for nuclear power may change this. Also, the problems and costs of constructing large industrial facilities in arid lands cannot be overestimated; they may be as problematical and expensive as production and transport of oil from Alaska and coal from Siberia. The large network of transmission lines, storage facilities, and pipelines will also cause disruption of regions and will experience increasing social resistance in some parts of the world [26].

Requirements for land (and perhaps ocean) areas will be extensive (Table 26). However, considering that almost 10% of the world's land mass is under cultivation and another 14% is partially used pasture, it seems reasonable to consider conversion of 1% of arid, nonproductive regions to solar-energy "farming" [5% corresponds to 50–100 TW(th) primary energy conversion]. Depending on the classification chosen (Fig. 18), the arid regions of the world, including the deserts, comprise 22–30 million square kilometers of land, or roughly 15–20% of total land.

In the United States the total present energy demands could be provided from high-efficiency solar-energy conversion systems sitting on less than 1% of the land (Table 27), compared with the 41% already committed to crops and grassland pasture. (For comparison, roads cover 1% of the continental U.S.). Even in Western Europe, where there is no Arizona, the present energy demand of France and Italy could be provided from high-efficiency solar conversion systems on about 1% of the land and on 3% of the land in West Germany (Table 28). Economic considerations, rather than availability of land, drive the rationale for a continental "helios strategy" for Central Europe.

Similarly, requirements for steel and concrete and other materials will be enormous—construction of 50 TW(th) of solar thermochemical hydrogen and solar thermal electric units plus the associated energy transport and storage elements will require

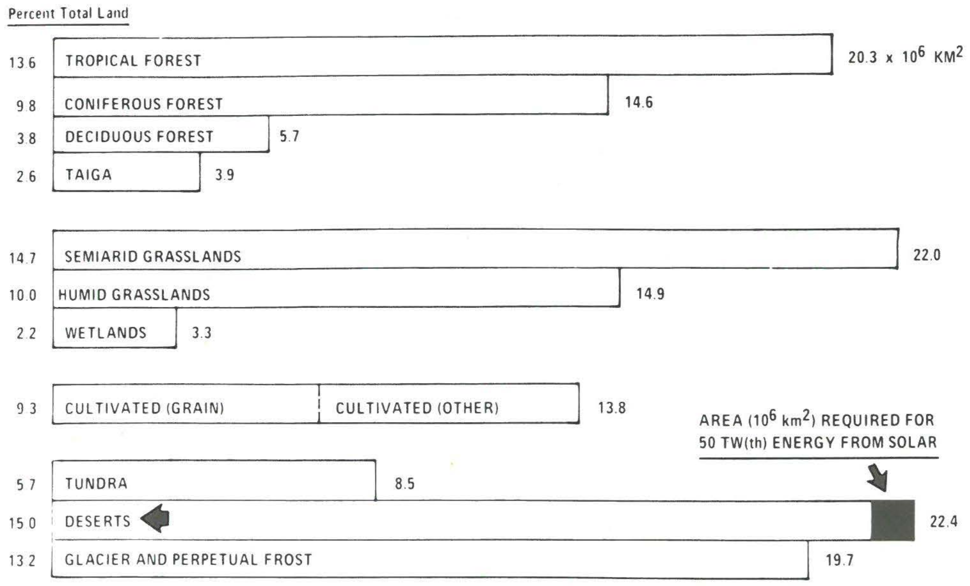



**Fig. 18. Global land classification by vegetation [81].**

**TABLE 27**

**Solar Energy Conversion and Land Use in the USA**

| Region | $10^6$km$^2$ | % Total | m$^2$/capita |
|---|---|---|---|
| Continental | 5.86 | 100.0 | 26,600 |
| Cropland | .95 | 17.0 | 4,500 |
| Grassland pasture | 1.40 | 24.0 | 6,380 |
| Woodland pasture | .16 | 2.7 | 718 |
| Other woodland | .13 | 2.2 | 585 |
| Farmsteads, roads | .07 | 1.2 | 319 |
| Grazing land | .74 | 12.7 | 3,378 |
| Forests | 1.23 | 21.0 | 5,586 |
| All other land | 1.13 | 19.3 | 5,133 |
| Solar electric[a] | .012 | 0.2 | 55 |
| Solar fuels[b] | .038 | 0.64 | 170 |
| Total solar for present energy demand | .05 | 0.84 | 225 |

[a] 1 kW(e)/capita average end use rate, net efficiency = 0.10 over dedicated land.

[b] Solar fuel production 50 W(th)/m$^2$ land.

**TABLE 28**

**Solar Energy Conversion and Land-Area Requirements in Europe**

| | West Germany | France | Italy |
|---|---|---|---|
| Population ($10^6$) | 62 | 51 | 54 |
| Primary energy use in TW(th) | 0.32 | 0.2 | 0.13 |
| Electricity production in TW(e) | 0.03 | 0.017 | 0.015 |
| Installed electric capacity GW(e) | 54 | 39 | 36 |
| Electric generation load factor | 0.54 | 0.44 | 0.43 |
| kw(th)/person | 5.2 | 3.9 | 2.4 |
| Area ($10^3$km$^2$) | 250 | 550 | 300 |
| Solar land[a] (nonelectric uses) in $10^3$km$^2$ (% total land) | 8.44 (3.4%) | 5.84 (1.1%) | 3.35 (1.1%) |
| Solar land[a] (electricity) | 1.16 (0.5%) | 0.68 (0.1%) | 0.62 (0.2%) |

[a] Assumes average insolation of 3.0 kwh/m$^2$-day, conversion efficiency = 20% for solar-derived energy.

20% of identified world iron resources if the present material intensive designs are retained. (Concrete, glass, and silicon are not resource-limited). Materials considerations are summarized in Tables 29–31. Even if the average system lifetime is 50 years, annual materials requirements for replacement in a steady-state situation would be a substantial fraction of present world production. World materials production will increase and, through refinement of engineering designs, materials requirements for solar technologies will decrease. So the requirements for structural materials, even at the level of 50 TW(th)—though substantial—does not seem unmanageable.

The energy investment (Table 29) in the construction of the plants is also within acceptable limits. With no decrease in materials requirements per kilowatt nor increase in the efficiency of materials production, the *direct* energy payback time for STEC and solar

**TABLE 29**

**Net Energy Analysis for McDonnell Douglas 15 MW(e) STEC**

| | kg/kW(e) | | | | |
|---|---|---|---|---|---|
| | Heliostat | Absorber | Storage | Total | kWh(th)/kW(e) |
| Steel | 121.0 | 5.3 | 17.6 | 143.9 | 1958. |
| Cement | 456.0 | — | — | 456.0 | 1277. |
| Aggregate | 569.0 | — | 639.0 | 1208.0 | 24. |
| Glass | 77.0 | — | — | 77.0 | 431. |
| | | | | | 3690. |

Time to repay primary energy displaced by solar power plant (load factor 0.27) = 0.5 years

TABLE 30

**Materials Requirements for Fission and Solar Power Plants (kg/kw$_e$)**

| Material | 1100 Mwe LWR[d] | STEC[a] | $R_1$ | $R_2$ |
|---|---|---|---|---|
| Concrete | 483 | 456 | 0.94 | 2.8 |
| Steel | 15[b] | 121[c] | 8.00 | 24.0 |
| Rebar | 11 | 5 | 0.45 | 1.3 |
| Glass | — | 77 | | |

[a] McDonnell Douglas 15-MW(e) solar thermal electric plant.
[b] Stainless steels.
[c] Low-carbon steel.
[d] Data from Bechtel Corporation.
[e] $R_1$ = Solar: nuclear materials ratio based on nameplate capacity.
[f] $R_2$ = Solar: nuclear materials ratio adjusted for 0.8 load factor for McDonnell STEC design (STEC includes only heliostat materials).

thermal hydrogen units located in high-insolation environments is 6 months. Indirect requirements for the energy for all industrial activities required for production of the facilities, including materials requirements, is estimated at approximately 18 months. Conventional silicon solar cells, by contrast, would require roughly 20 years to repay the energy consumed in their production, but detailed calculations [50] indicate that EFG silicon cells would have a payback time of 2 years (Table 32), including all activities related to material and cell production. Similarly, OTEC plants are estimated to have a payback time of approximately one to two years [53, 75].

Operation of solar energy systems and the industrial infrastructure required for their construction and replacement will have environmental consequences, in spite of some widely prevailing myths that solar technologies will be relatively benign. We know that new technology, when used on a large scale, will often have unexpected and sometimes unwanted consequences [10]. Davidson and Grether [16] have estimated some of the impacts associated with construction of STEC central receiver plants of present design. Fragile desert ecosystems would be severely impacted during construction, with the fine desert crust broken, leading to erosion and dust. The habitats of burrowing animals would

TABLE 31

**Materials Requirements to Construct 10 GW(e) STEC Plants per Year[a]**

| Material | (a) Mtons/year (STEC) | (b) U.S. production | (a)/(b) |
|---|---|---|---|
| Steel | $1.44 \times 10^6$ | $1.4 \times 10^8$ | 0.01 |
| Cement | $4.56 \times 10^6$ | $9.0 \times 10^7$ | 0.05 |
| Sand, gravel | $12.0 \times 10^6$ | $9.5 \times 10^8$ | 0.01 |
| Glass | $0.77 \times 10^6$ | $1.2 \times 10^7$ | 0.06 |

[a] Materials requirements for 15 MW(e) McDonnell-Douglas design; U.S. production in Mtons/year; cement + sand + gravel = concrete; U.S. production for 1973.

**TABLE 32**

**Silicon Solar Cell Energy Payback Characteristics**

| Process | Energy payback time (years) |
|---|---|
| Conventional—solar cells for space vehicles | 40 |
| Conventional—improved production efficiency | 15 |
| EFG ribbon (present process) | 2 |
| EFG ribbon (improved process) | 1 |

*Source:* Mobil-Tyco Solar Energy Corporation, 1977.

be destroyed and the ecology of the region permanently altered. While on the national scale, additional air pollution resulting from production of glass, concrete, and steel for the solar plants would not be substantial, the *local impact* of these emissions would constitute an environmental charge against the facilities.

Because the systems will require energy transport and storage, other environmental impacts, such as the flooding of valleys to provide pumped hydrostorage units, and the esthetic impacts of long-distance high-voltage transmission lines will arise, often at long distances from the solar conversion facilities themselves.

Potential climatic effects exist with many of the solar technologies. For example, STEC, PV, and solar hydrogen systems will modify (Fig. 19) both the boundary conditions and energetics of the climatic system [74]. Surface albedo (Fig. 20) and surface roughness will be altered, as will surface hydrology in nonarid regions. Solar radiation may be converted to latent heat through evaporative cooling (especially for solar electric facilities located in coastal desert regions). Ocean thermal electric conversion systems will decrease the surface temperature of the tropical oceans by as much as a few tenths of a degree Celsius, sufficient to cause large climatic changes on the synoptic scale [77] and may also change the ocean/atmosphere equilibration dynamics of carbon dioxide leading to an increased atmospheric carbon-dioxide burden. All of this deserves close attention. The potential climatic effects of these physical changes, especially when modification of as much as one million square kilometers may be involved, are virtually unknown, and there has been little effort to investigate them.

Solar energy systems will also be important because of what they *do not do*. There is rapidly growing agreement [3, 59] that the increasing atmospheric carbon-dioxide levels associated with fossil-fuel combustion presents a potentially severe threat to mankind via massive changes in the climatic system within a century, if present trends in fossil-fuel use are not modified. It may prove necessary to consider the large scale use of both fission and solar energy systems in order to minimize the risks associated with these severe climatic changes.

### MARKET PENETRATION

Many scenarios and projections for the contribution of solar energy in the United States have been made. Some of these are shown in Fig. 21. These show enormous dispersion, as do current forecasts of total energy demand. For other countries also beginning an assessment of the potential role of solar energy conversion, the situation is similar. Something better is needed. The history of the energy marketplace in the industri-

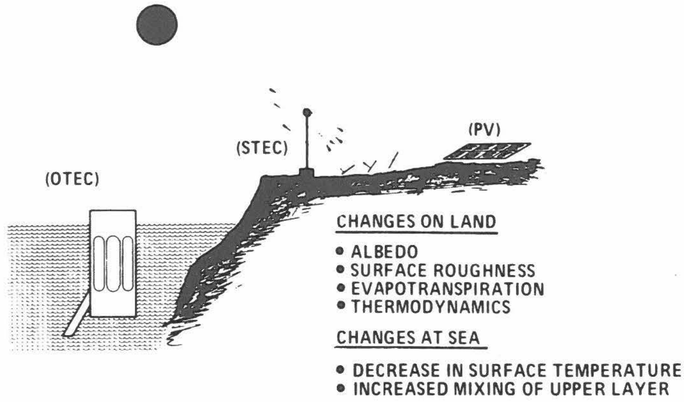



**Fig. 19. Modifications of the climatic system by solar energy conversion machines.**

alized world demonstrates that four to five decades are required before new energy technologies can command a substantial fraction (30–50%) of total primary energy use. Although the future of solar technologies can hardly be predicted, it *is* possible to estimate the maximum contribution they would have if technical feasibility, economic competitiveness and social and environmental acceptability were high.

Marchetti [47], following the discovery of Fisher and Pry [24] that many competitive market substitutions are logistic, has found that the energy marketplace of most industrialized nations, and of the world, is also logistic. This means that both the rise and fall of market share of wood, coal, oil, and natural gas are both accurately described *over the long term* by

$$f/(1 - f) = \exp A(t - T),$$

where $f$ is the fraction of the total energy captured by a specific primary source and $T$ and $A$ are constants that differ for the various primary energy sources and for the period of concern (entry or exit).

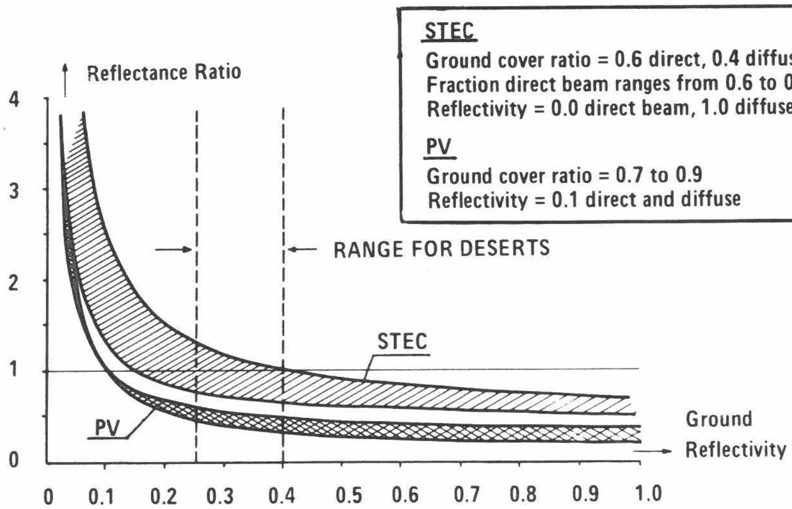



**Fig. 20. Reflectance ratio for STEC and PV power plants.**

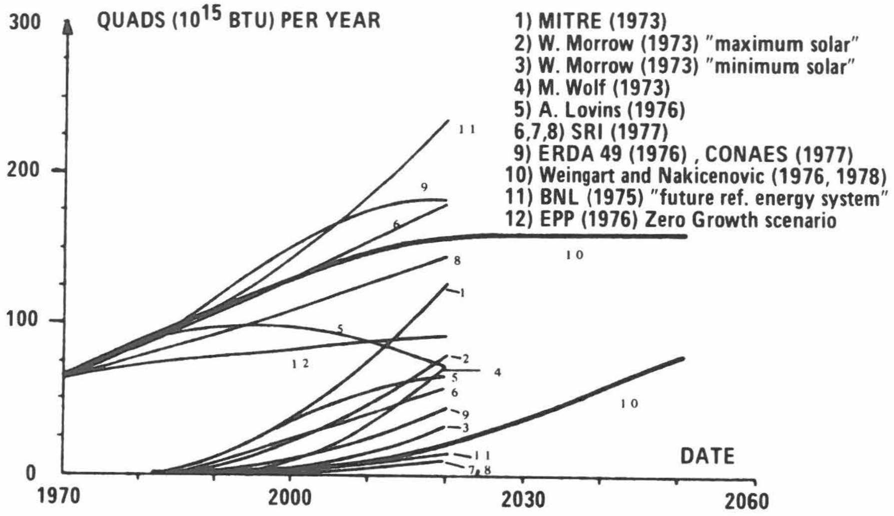



**Fig. 21. Scenarios and projections of total energy demand and the share potentially available from solar energy (U.S.A.) [76].**

This remarkable behavior is shown in Fig. 22 for the United States and in Fig. 23 for the world. The multidecade time constants presumably reflect the inertia in large, complex social systems (national economies or the world economy). The logistic structure probably is a manifestation of a complex learning process, in which a society ''learns'' to make use of a new technology on a substantial scale. I believe that we can expect the penetration of solar and nuclear technologies also to follow this behavior. Assuming (optimistically) that some mix of solar technologies were to provide 1% of U.S. energy needs by 1985 and that subsequent energy market penetration could proceed at a rate somewhat greater than has already occurred with oil and natural gas, it would *still require 65 years before solar energy could displace 50%* of national energy use. On the global scale, assuming 1% solar energy by the year 2000 and a logistic behavior consistent with the dynamics of the world energy market place over the past 130 years, it would require somewhat more than a century before a 50% displacement was reached. This means that large scale use of this option under the best (and by no means certain) of technical, economic, social, and institutional conditions will take a long time to be realized. Similar considerations are true for fission and will also be true for fusion.

A careful review and analysis [76] of virtually all available solar energy market penetration scenarios for the United States suggests that most current projections including federal goals for the years 2000 and 2020 are ahistorically optimistic (i.e., unrealistic). On the positive side, the evidence suggests that if development of a mix of solar technologies suitable for use at the global scale is strongly supported during the next several decades, sunlight could be providing the majority of world energy needs by the time fossil fuels are largely depleted. In this perspective, fission power systems, which for political and other reasons may be used on a very large scale over the coming century, may only be a transitional energy option on the way to a global solar economy.

## Conclusions

The time available to make the transition from traditional fossil fuels to primary sources capable of sustained support of the human ecosystem is roughly coincident with

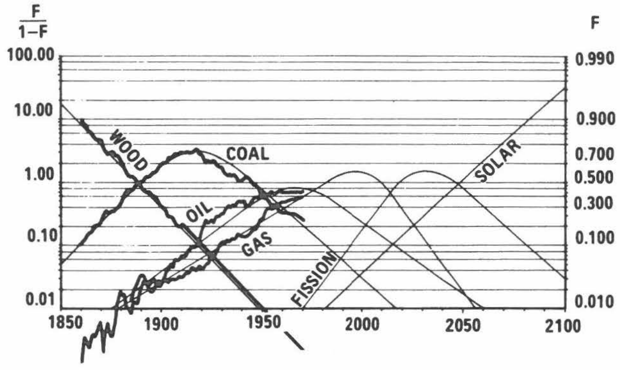



**Fig. 22. Market penetration history and projection for the U.S.A.**

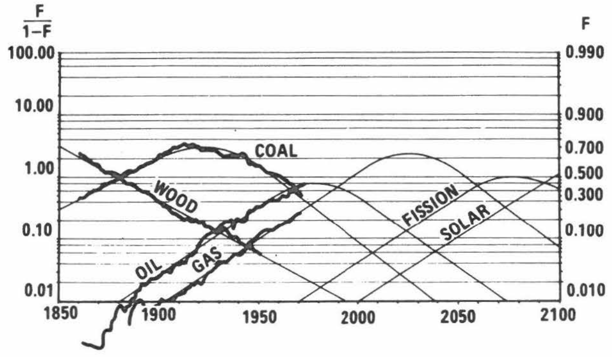



**Fig. 23. Energy Market penetration history and projection for the world.**

the period required for new energy technologies to take over. The uncertainties surrounding the large-scale future energy options make it imperative that we develop in parallel a multiplicity of options. Solar energy, through direct conversion in high-efficiency systems, can be used, in principle, as the source of necessary secondary energy at the scale of 100 TW(th). This potential demands that we support the development of a large menu of solar options as vigorously as we did the fission technologies. Fortunately, this is beginning to occur internationally, but insufficient emphasis has been placed on fuel and electricity production options, and there has been almost no attention to the possibility of large-scale strategies. Detailed regional and international systems studies should be initiated (including a "WAES for sunlight"), to set the stage for rational programs of technical development that could lead to new possibilities for mankind, to provide the metabolic basis for a stable, sustainable world.

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