THE HELIOS STRATEGY

An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet

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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 (Brown, 1976). 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. A great challenge to our technological and social ingenuity 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 percent 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 cent per year leads to 13 TW(th) demand by 2027 and 20 TW in 2077. This 20 TW(th) might correspond to a 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 percent, less than the 5 percent 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 (Wilson, 1977). 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 (Grenon et al, 1976) suggest that as little as 15 to 25 percent 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, non-traditional fossil fuels and uranium in non-breeder 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, (Gerlach, 1976; 1977) environmental, economic 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

PRESENT WORLD USE & RESERVES OF TRADITIONAL FOSSIL AND RENEWABLE ENERGY RESOURCES

	TW(th)	TW(th)-yr.
Oil & Natural Gas[1]	4	200 - 400
Coal[2]	2	2,000[2]
Hydropower	1	Renewable
Wood[3]	0.3 - 1	Renewable

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1 Secondary and tertiary recovery possibilities not adequately included in these estimates

2 WAES: ~1/5 of all coal in place assumed ultimately recoverable

3 Primarily non-commercial uses

Note: WAES stands for Workshop on Alternative Energy Strategies. See (Wilson, 1977)

NOTE: 1 TW = 10^{12} W

Table 1

PRESENT SITUATION AND THREE SCENARIOS FOR

GROWTH OF TOTAL PRIMARY ENERGY PRODUCTION

SCENARIO	GROWTH RATE	PROJECTED WORLD ENERGY DEMAND [1] 2027	2077	SCENARIOS FOR 2077 WORLD POPULATION	PER CAPITA ENERGY USE
1. LOW	0.9 %	13	20	6×10^9	3.3 kW(th)
2. MEDIUM	2.0 %	22	60	10×10^9	6. "
3. HIGH	3.3 %	41	200	20×10^9	10. "
				1977	
PRESENT SITUATION[2]	5 % (2.0 %)	8		4×10^9	2. kW(th)

1 TW(th) rate of mobilization of primary sources in thermal equivalent terms

2 The higher growth rate has prevailed over the past several decades; long term average for past 150 years, including use of wood, is 2.0 %.

Table 2

CHARACTERISTIC TIME[1] TO EXHAUST KNOWN FOSSIL RESOURCES

Resource[2]	Reserves TW(th)-yr	Characteristic Time (Years) At Various Growth Rates				
		0%	1%	2%	3%	4%
Oil & Gas	400- 800	50 100	41 69	35 55	31 46	27 40
Coal	2000[3]	250	125	90	71	60
Oil, Gas & Coal	~3000	375	156	107	84	69

1 $T = g^{-1} \ln [1 + Rg/P_o]$

where g = growth rate

R = Reserves in TW(th)-yr.

P_o = 8 TW(th)

and $P(t)$ = Rate of primary energy consumption is assumed exponential

$= P_o \exp(gt)$

2 WAES, 1977

3 20% of total in-place coal reserves (10,000 TW(th)-yr.) assumed recoverable

Table 3

development of the region, but it will occur globally, and it will be essentially completed within a century or so.

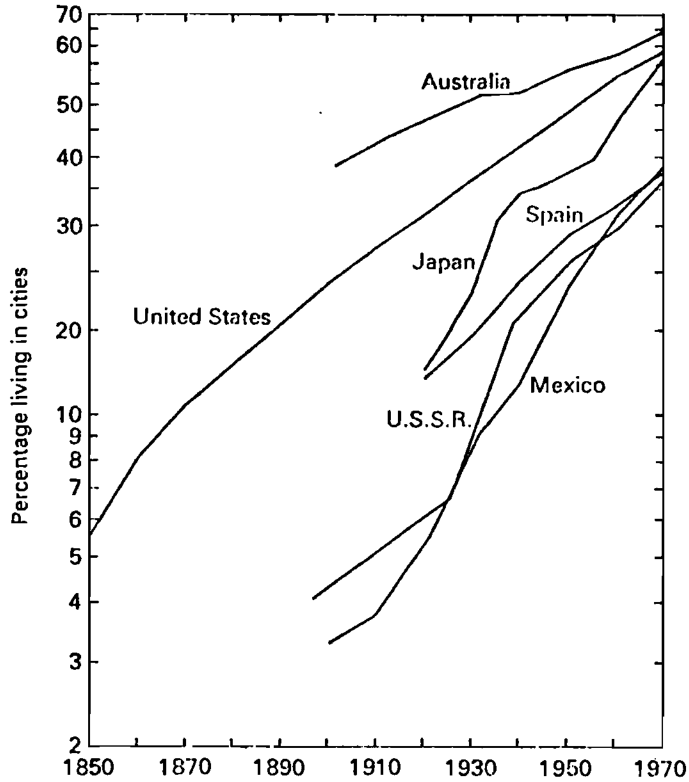
This transition will be constrained by other evolutionary changes in the human environment. Over the past century the industrialized nations have experienced an unprecedented and seemingly inexorable demographic shift towards urbanization (Davis, 1973), with a quarter of all people and well over 50 percent of the population of most developed countries now living in cities of 100,000 or more (Figure 1). Human settlements themselves are becoming increasingly complex, technological, dense and spatially extensive (United Nations, 1976). Doxiadis and Papaioannou (1974) argue that this trend will continue through the evolution (Figure 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" (Figures 3 - 6).

The infrastructures which 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, 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 (Marchetti, 1975), 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, <u>must be converted on the necessary scale to these secondary carriers</u>.

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 <u>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</u>. 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 DEMOGRAPHIC SHIFT TOWARDS URBANIZATION



Ref: Davis, 1973 (Reproduced through courtesy of SCIENTIFIC AMERICAN)

Figure 1

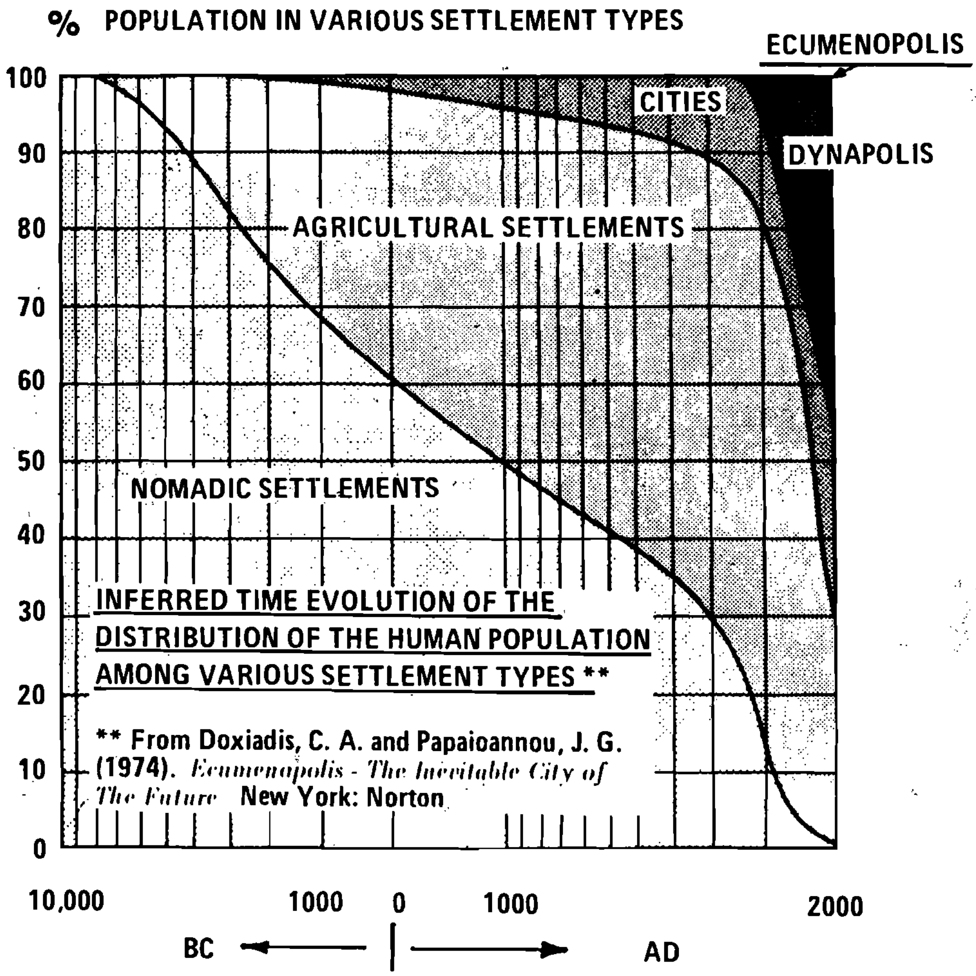

% POPULATION IN VARIOUS SETTLEMENT TYPES
ECUMENOPOLIS
CITIES
DYNAPOLIS
AGRICULTURAL SETTLEMENTS
NOMADIC SETTLEMENTS
INFERRED TIME EVOLUTION OF THE DISTRIBUTION OF THE HUMAN POPULATION AMONG VARIOUS SETTLEMENT TYPES **
** From Doxiadis, C. A. and Papaioannou, J. G. (1974). Ecumenopolis - The Inevitable City of The Future New York: Norton
100
90
80
70
60
50
40
30
20
10
0
10,000
1000
0
1000
2000
BC
AD

Figure 2

ECUMENOPOLIS IN U.S.A. AFTER 2100

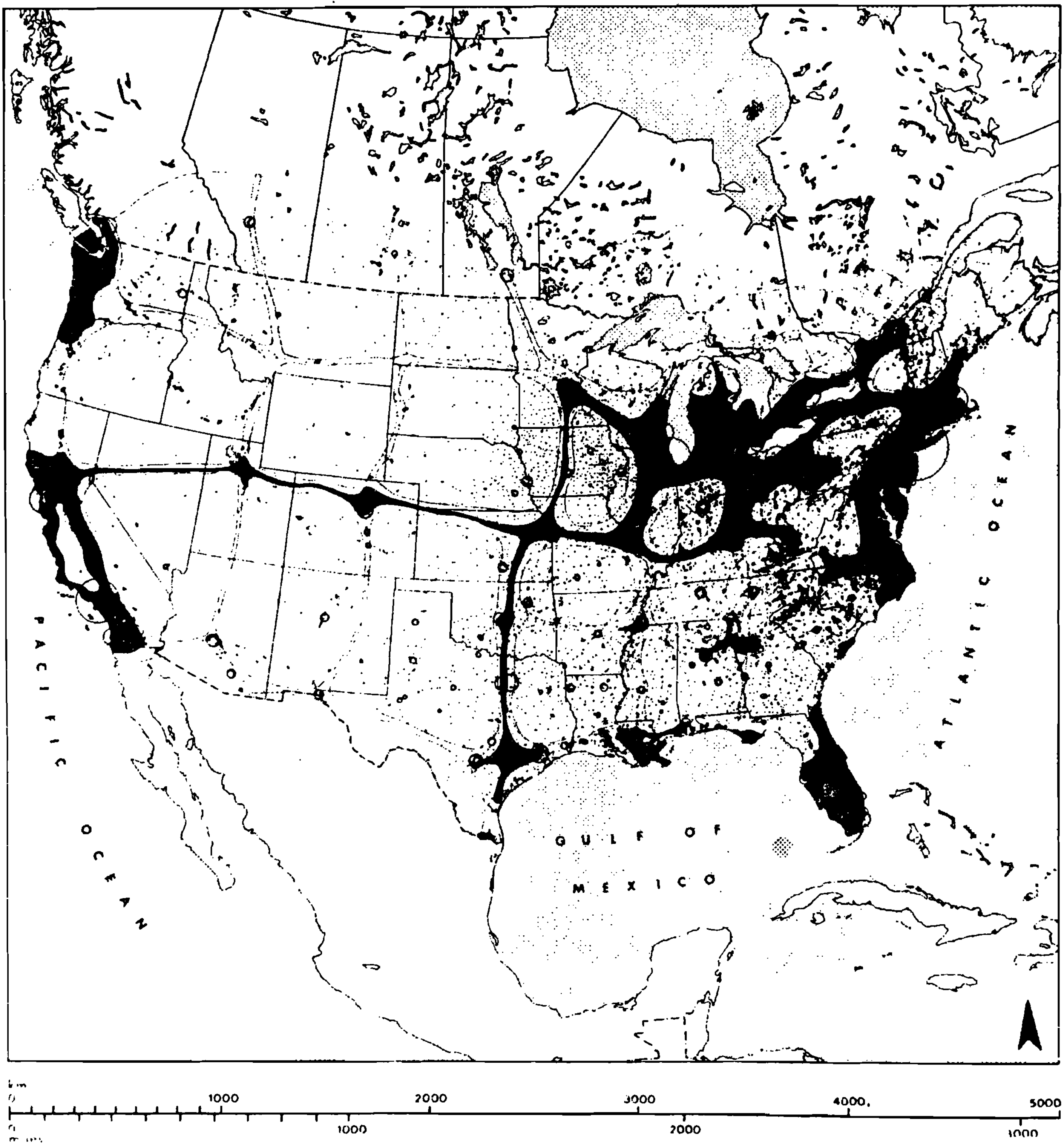


Figure 3

ECUMENOPOLIS 2100

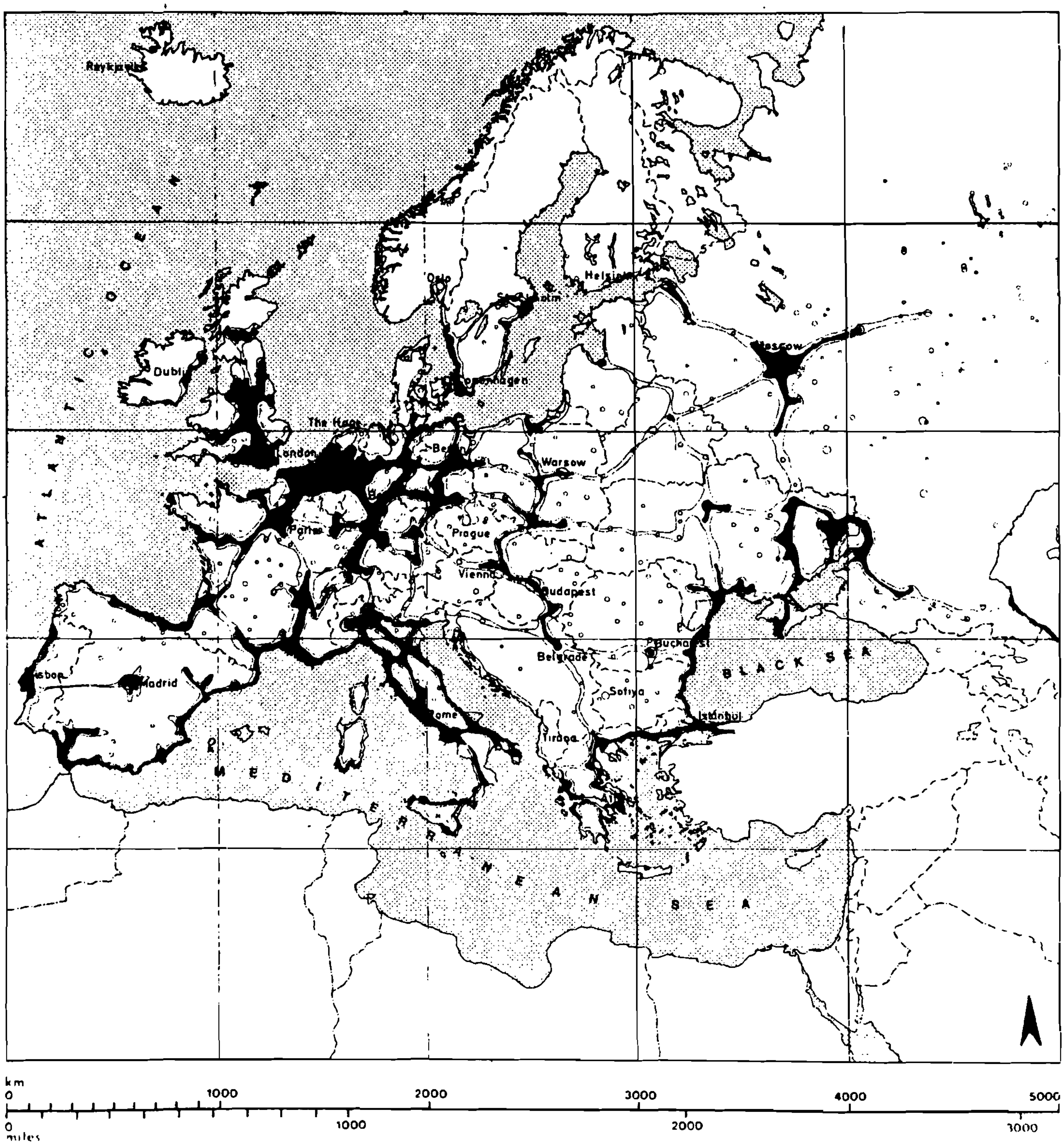


Figure 4

ECUMENOPOLIS 2100 (FROM DOXIADIS)

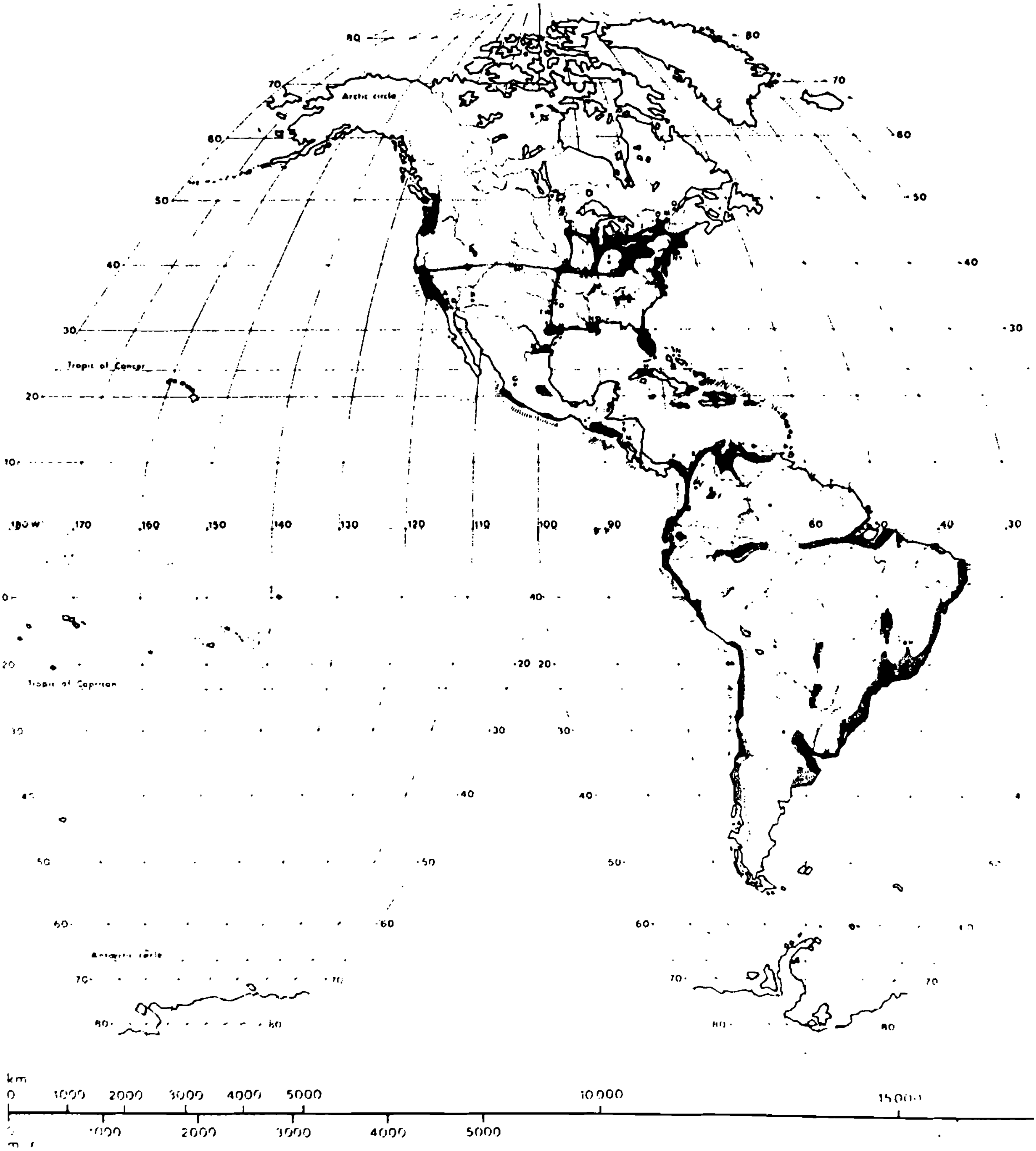
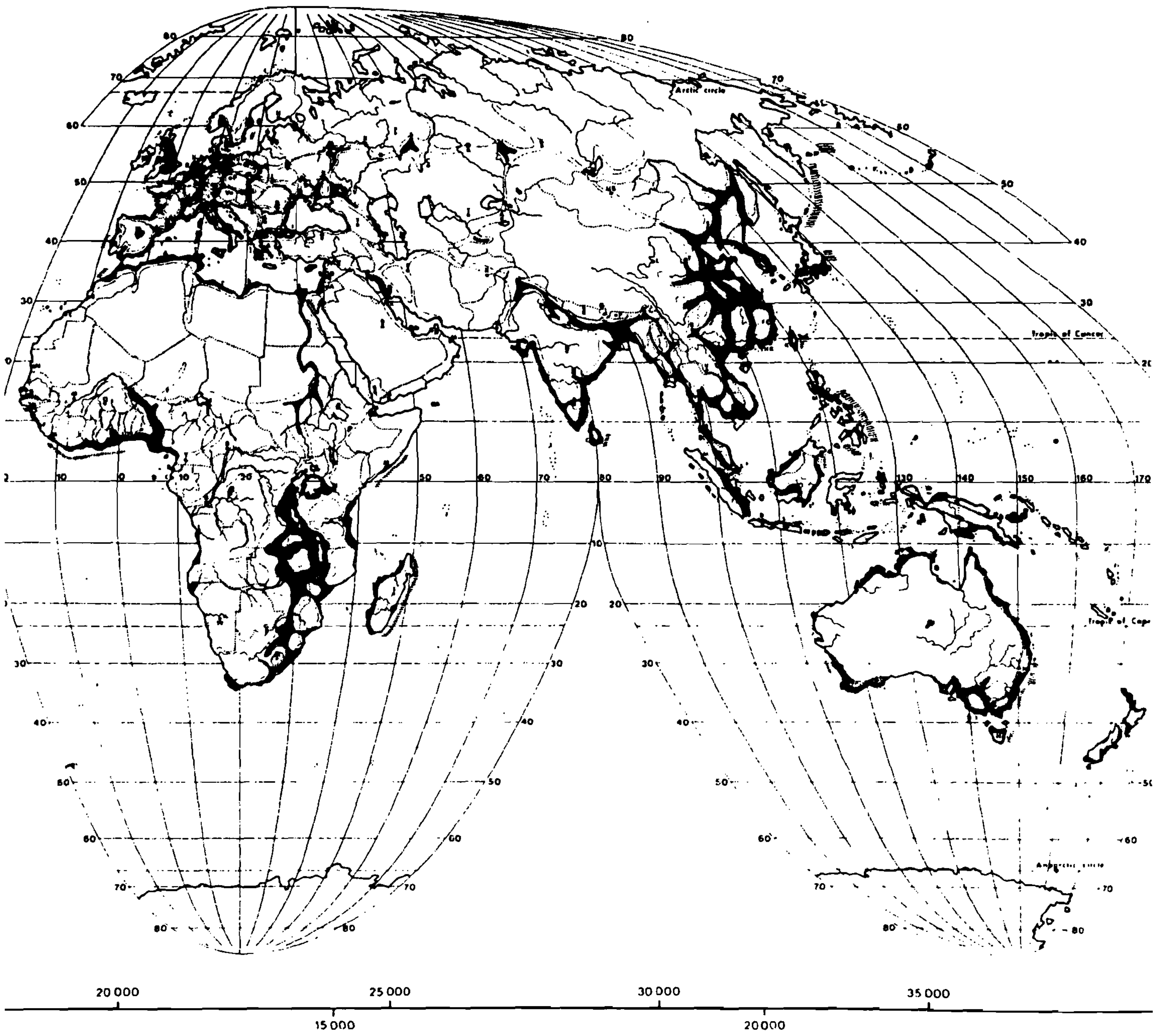


Figure 5

ECUMENOPOLIS 2100
(FROM DOXIADIS)



relative degree of elaboration by region (highest = 1)

Figure 6

TRANSPORTABILITY OF SECONDARY ENERGY (km)[1]

MECHANICAL ENERGY (Cables, Compressed air)	1 - 10
THERMAL ENERGY (District Heating Systems)	10 - 50
ELECTRICITY[2] (Bulk Transport)	up to 5000
CHEMICAL FUELS & NEGENTROPY	5000 (gas pipeline) global (liquid fuels, negentropy as liquid air)

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1 Present technology except for 2

2 Present average distance for bulk transport is ~100 km. Present HVDC transmission technology is ~3000 km. 5000 km can be expected by 2000.

Table 4

the future (Haefele, 1976; Starr, 1976, Weinberg, 1976). Solar energy as a possible global energy source at the 10 to 100 TW(th) scale is often rejected on a combination of technical, economic and logistic grounds.

Others (Lovins, 1976a, 1976b; Hayes, 1977, Reuyl, 1977) 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 otners (Mesarovic and Pestel, 1974) 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.

ENERGY PRODUCTION FROM RENEWABLE AND LARGE-SCALE ENERGY SOURCES IN THE ASYMPTOTIC PHASE

SOURCE	PRODUCTION RATE TW(th)
TIDAL	$\ll 1$
GEOTHERMAL	$\sim 1-5$
FISSION (FBR)	> 100
FUSION	> 100
SOLAR:	
INDIRECT	10–20
DIRECT	> 100

Table 5

SECONDARY ENERGY PRODUCTION FROM SOLAR ENERGY CONVERSION SYSTEMS

RESOURCE	TECHNOLOGY	EFFICIENCY[1]	GROUND COVER	SECONDARY ENERGY	$W(th)/m^2$ DEDICATED LAND, SEA	W/m^2 SOLAR MACHINE
DIRECT BEAM $7 - 8\ kWh/m^2$-day $290 - 333\ W/m^2$	STEC	0.15 - 0.25	0.4 - 0.6	ELECTRICITY	50 - 150	44 - 83 (e) 130 - 250 (th)[2]
	ST-H_2	0.20 - 0.60	0.4 - 0.6	HYDROGEN	24 - 120	60 - 200 (th)
GLOBAL RADIATION $2 - 6\ kWh/m^2$-day $83 - 250\ W/m^2$	SOLAR HEATING	0.20 - 0.35	N/A	LOW GRADE HEAT (<100C)	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	.10 - 0.25	0.4 - 0.9	ELECTRICITY	10 - 216	8 - 80 (e) 24 - 240 (th)
OCEAN THERMAL GRADIENTS	OTEC[4]	0.03	4 PLANTS/ $10^3\ km^2$	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) [3]

(1) Conversion from the resource to secondary energy

(2) 1 kW(e) is assumed equivalent to 3 kW(th)

(3) 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, produces 100 kW(e) in a wind of 8m/sec. Down-stream spacing is assumed to be ten blade diameters, adjacent spacing 2 - 10 diameters, depending on the directional variability of the wind.

(4) $30\ km^2/100\ MW(e)$

Table 6

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 which 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 (upwards of 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 or (if ever available) fusion alternatives (Haefele et al., 1977). 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.

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 non-storability 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, 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 (Holling, 1976; Weingart, 1977a) which 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:

Local use of solar-generated heat for space heating, water heating and industrial processes where economically and logistically suitable.

Local and regional use of small-scale mechanical, electrical and fuel generating units, especially in developing countries.

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.

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 percent) 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 (Aerospace, 1976; Tarnizhvskii and Smirnova, 1974). Hydrogen can be transported over continental distances of 5,000 kilometers or more, with available or developable pipeline system technologies. Hydrogen, widely regarded as the gaseous energy carrier of the future (Veziroglu, 1974, Bockris, 1975), 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 to 10 percent 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 (Figure 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 twenty billion people (Doxiadis and Papaioannou, 1974).

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) which respond only to direct beam sunlight, location in arid, sunny regions will be essential.

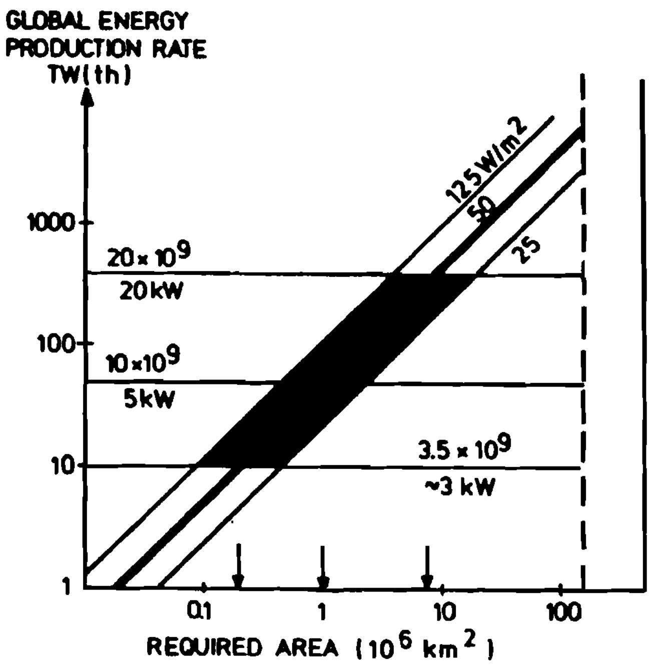
Long distance transport permits such a siting strategy. All of Europe is within practical high voltage transmission distances of Portugal, Spain and Turkey; in a few decades undersea cable from North Africa could also bring solar electricity to Europe. With the exception of Japan, which must be served by liquid fuels via tanker, virtually the entire world is within practical hydrogen pipeline transport distances (5,000 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, 5,000 km hydrogen transport using 48 inch pipeline would cost about $ 3 per barrel (Gregory, 1976; Bockris, 1975; Dickson et al, 1977) and the use of geophysical storage would add approximately $1 per barrel (Figure 8).

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.

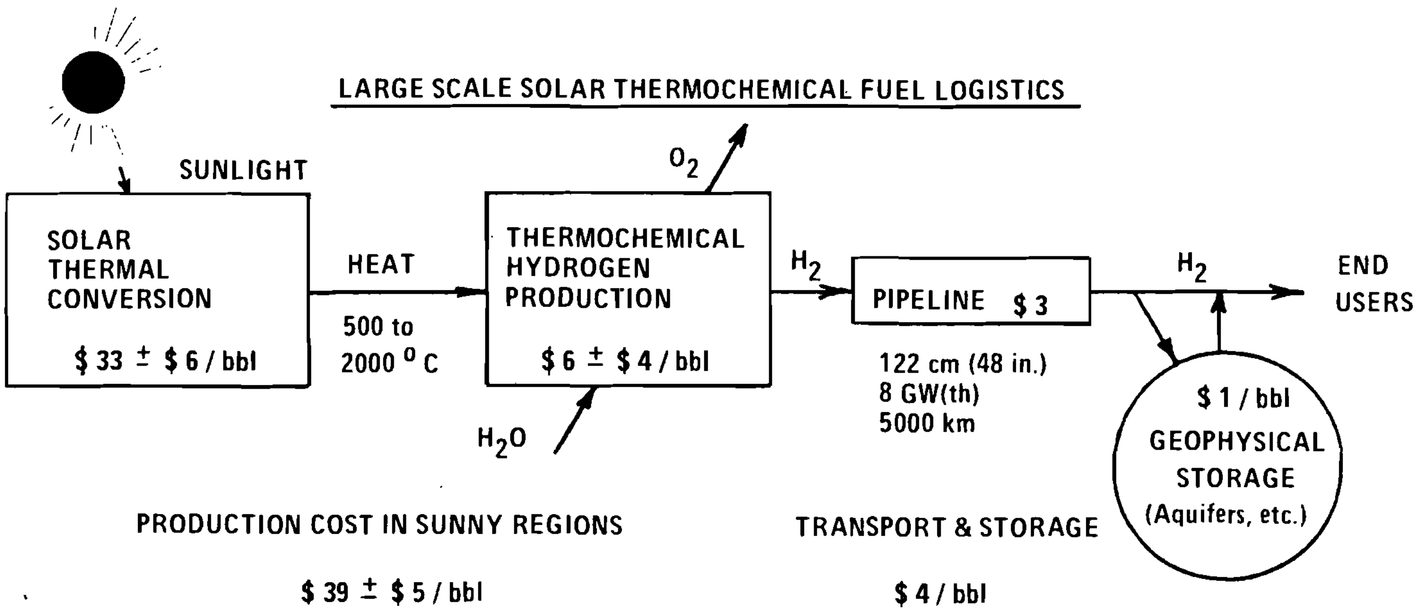
The asymptotic mix of solar technologies would depend in part on the required total rate of secondary energy production. The use of indirect forms of sunlight (hydropower, ocean thermal gradients, wind and waves) appears limited to something on the order of a few tens of TW(th) at most (Table 7), and some argue that wind, waves and OTEC combined are unlikely ever to

SOLAR ENERGY CONVERSION LAND AREA REQUIREMENTS



(Arrows indicate land area requirements for solar conversion systems producing secondary energy at the rate of 50 W(th) per sq. meter of dedicated land, to supply a total demand of 10, 50 and 200 TW(th) respectively)

Figure 7



LARGE SCALE SOLAR THERMOCHEMICAL FUEL LOGISTICS
SUNLIGHT
SOLAR THERMAL CONVERSION
$ 33 ± $ 6 / bbl
HEAT
500 to 2000 °C
O_2
THERMOCHEMICAL HYDROGEN PRODUCTION
$ 6 ± $ 4 / bbl
H_2O
H_2
PIPELINE $ 3
122 cm (48 in.)
8 GW(th)
5000 km
H_2
END USERS
$ 1 / bbl
GEOPHYSICAL STORAGE
(Aquifers, etc.)
PRODUCTION COST IN SUNNY REGIONS
$ 39 ± $ 5 / bbl
TRANSPORT & STORAGE
$ 4 / bbl

Figure 8

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

Table 7

contribute more than a few TW(th) (Weinberg, 1976). 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 TW(th) to 100 TW(th) or more, comparable with the potential from the fast breeder and fusion.

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 Europe form partnerships with sun-rich neighbors. For example, a technical and economic partnership between the Federal Republic of 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 LDC's 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 (Caputo, 1977).

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 be 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 which are inherently large in their 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 maintanence. As the systems grew along with a village (if growth occurs and if literacy and wealth increased), 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 (Rogers, 1972, 1974) which 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 (Eckholm, 1976; Makhijani, 1975) 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 valuble 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 (Wade, 1975b) 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, a possible 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 which 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 which 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.

The 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 TW(th) to 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 which 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 (1976) have shown that a very modest difference in social discount rates (Table 8) in favor of solar technologies would result in solar thermal electricity and the fast breeder reactor having essentially comparable costs (Figure 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, <u>even</u> if direct costs were the only criterion.

<u>The Solar Resource</u>

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 (Figure 10), even after passing through the atmosphere, permits the generation of heat at temperatures over the entire range required by industrial society (Figure 11).

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 per sq. meter and rarely exceeds 1 kW per sq. meter 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 hours) between 80 and 240 watts per

ESCALATION RATES USED IN CAPITAL COST PROJECTIONS (%)

• 5% GENERAL PRICE INFLATION ASSUMED

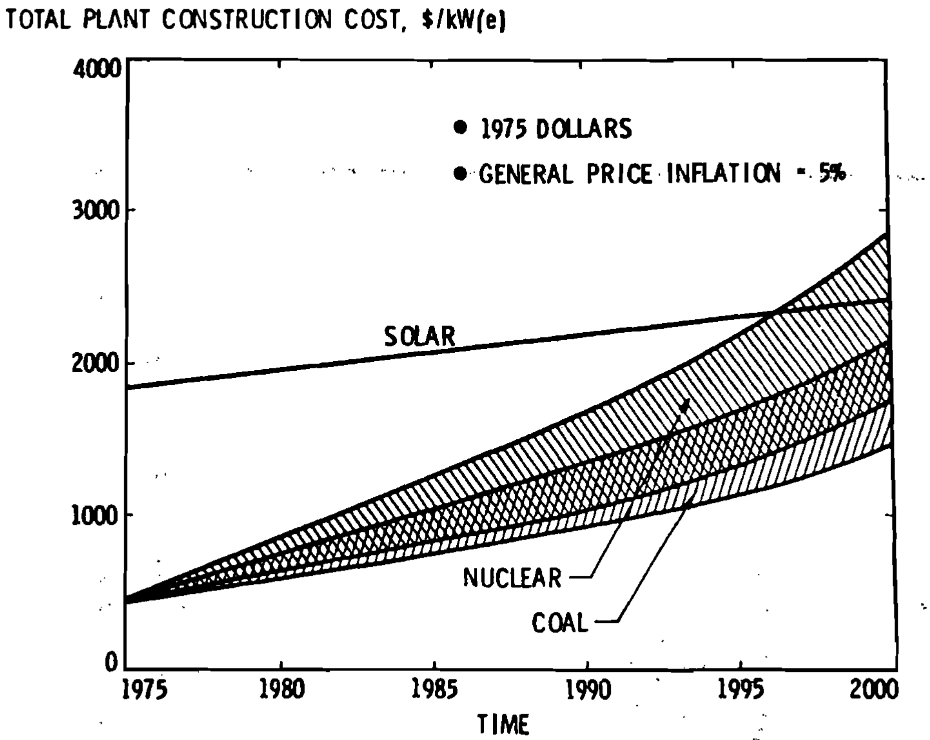
	1975-1980	1980-1990	1990-2000
UPPER LIMIT- BROAD BUT DECREASING SOCIAL RESISTANCE			
NUCLEAR	17	13	10.75
COAL	15	12	10.0
LOWER LIMIT- LONG-TERM PROJECTED RATES ADOPTED IMMEDIATELY			
NUCLEAR	10.75	10.75	10.75
COAL	10.0	10.0	10.0
SOLAR- ASSUMED TO BE SOCIALLY ACCEPTABLE			
	6.2	6.2	6.2

Courtesy NASA/JPL

Source: Caputo (1976)

Table 8

PROJECTIONS OF CAPITAL COST



From: Caputo, R.S. and Truscello, V. C. (1976). "Solar Thermal Electric Power Plants – Their Performance Characteristics and Total Social Costs <u>Proc. 11th IECEC</u> (USA)

Figure 9

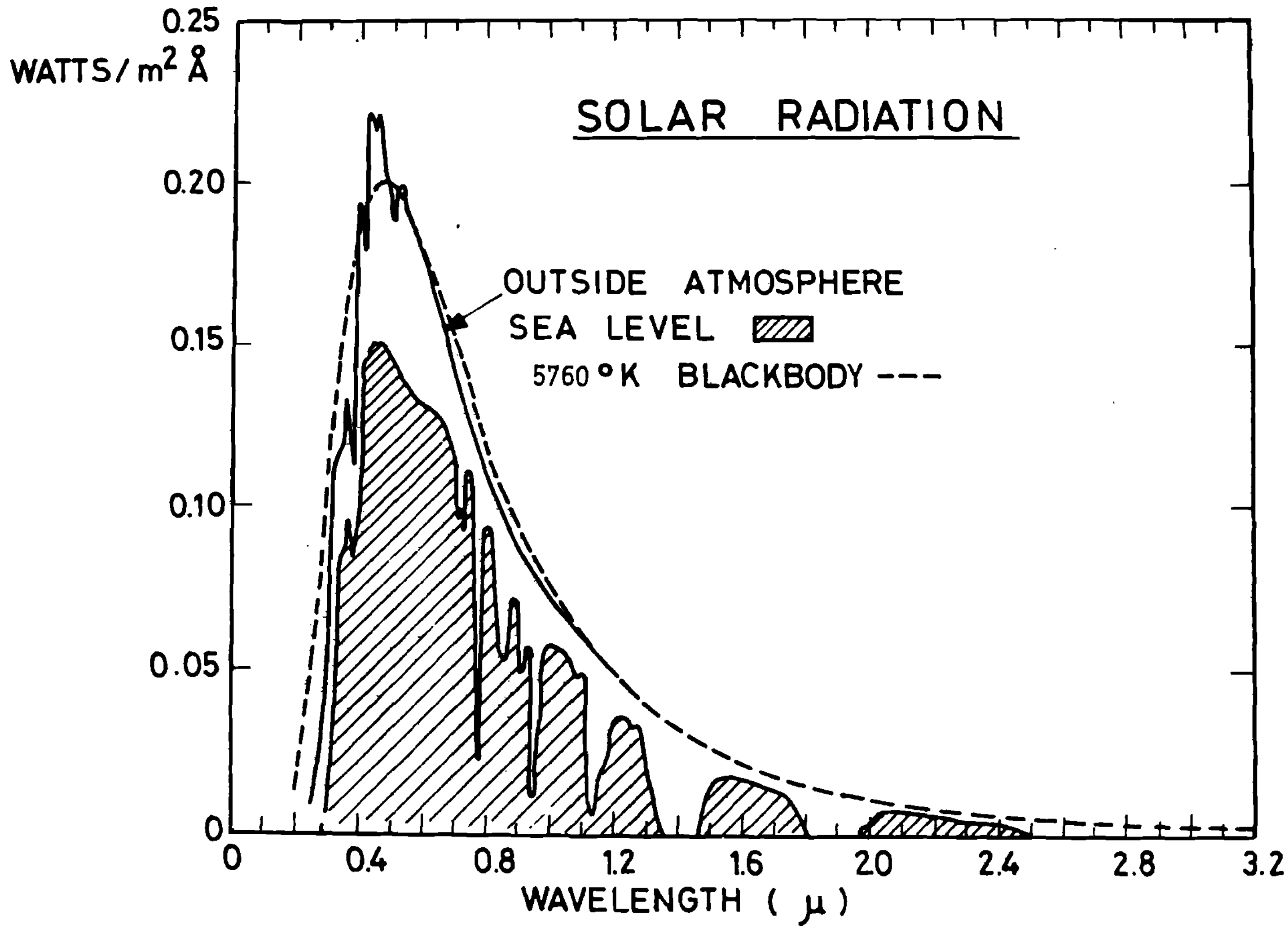

SOLAR RADIATION
OUTSIDE ATMOSPHERE
SEA LEVEL
5760 °K BLACKBODY ---
WATTS / m² Å
0.25
0.20
0.15
0.10
0.05
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
WAVELENGTH (μ)

Figure 10

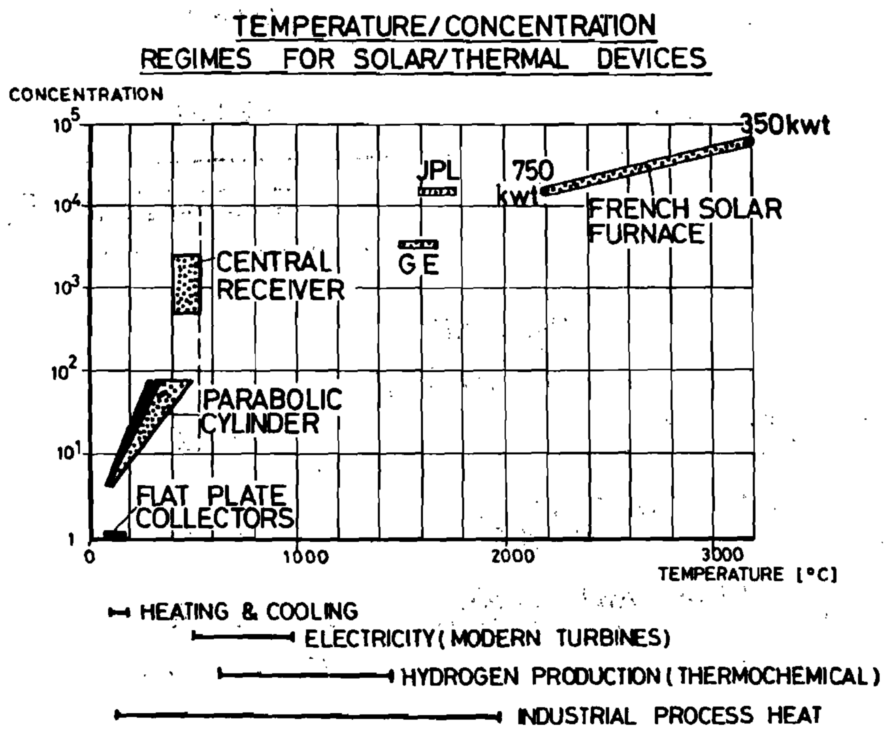

TEMPERATURE/CONCENTRATION
REGIMES FOR SOLAR/THERMAL DEVICES
CONCENTRATION
10^5
10^4
10^3
10^2
10^1
1
0
1000
2000
3000
TEMPERATURE [°C]
350kwt
JPL
750 kwt
FRENCH SOLAR FURNACE
GE
CENTRAL RECEIVER
PARABOLIC CYLINDER
FLAT PLATE COLLECTORS
HEATING & COOLING
ELECTRICITY (MODERN TURBINES)
HYDROGEN PRODUCTION (THERMOCHEMICAL)
INDUSTRIAL PROCESS HEAT

Figure 11

CHARACTERISTICS OF SOLAR RADIATION AS AN ENERGY RESOURCE

THE SOLAR CONSTANT	1353 W/m^2
EFFECTIVE RADIATION TEMPERATURE OF THE SUN	5760 K
MAXIMUM DIRECT BEAM IRRADIATION AT SEA LEVEL	~1000 W/m^2

REGION, IRRADIANCE		kWh/m^2–DAY	W/m^2 (AVERAGE)
TROPICS, DESERTS	(ANNUAL AVERAGE HORIZONTAL)	5 – 6	210 – 250
TEMPERATE ZONES	(ANNUAL AVERAGE HORIZONTAL)	3 – 5	130 – 210
LESS SUNNY REGIONS (e.g. NORTHERN EUROPE)	(ANNUAL AVERAGE HORIZONTAL)	2 – 3	80 – 130
AVERAGE ANNUAL DIRECT BEAM IRRADIANCE IN SUNNY REGIONS		7 – 8	290 – 330
MONTHLY AVERAGE DIRECT BEAM RADIATION IN SUNNY, ARID REGIONS		5 – 10	210 – 420

Table 9

square meter, characteristic of Northern European and sunny, arid regions respectively. At normal incidence, the average direct beam or focusable radiation is as high as 330 watts per square meter (continuous averaged power) in clear sky environments such as deserts, but falls to little more than 100 watts per square meter 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 (Weingart, 1977a). There are two general possibilities - those which convert radiant solar energy directly and those which 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 Figure 12, is shown in Figure 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 (Figure 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 to 50 percent of all primary energy is used for low-grade end uses (<100 deg. C), primarily space heating. Another 20-25 percent is for industrial process heat above 100 deg. C. (Basile, 1976). 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 (DeWinter and DeWinter, 1976). Dozens of prototypes (Figure 14) and thousands

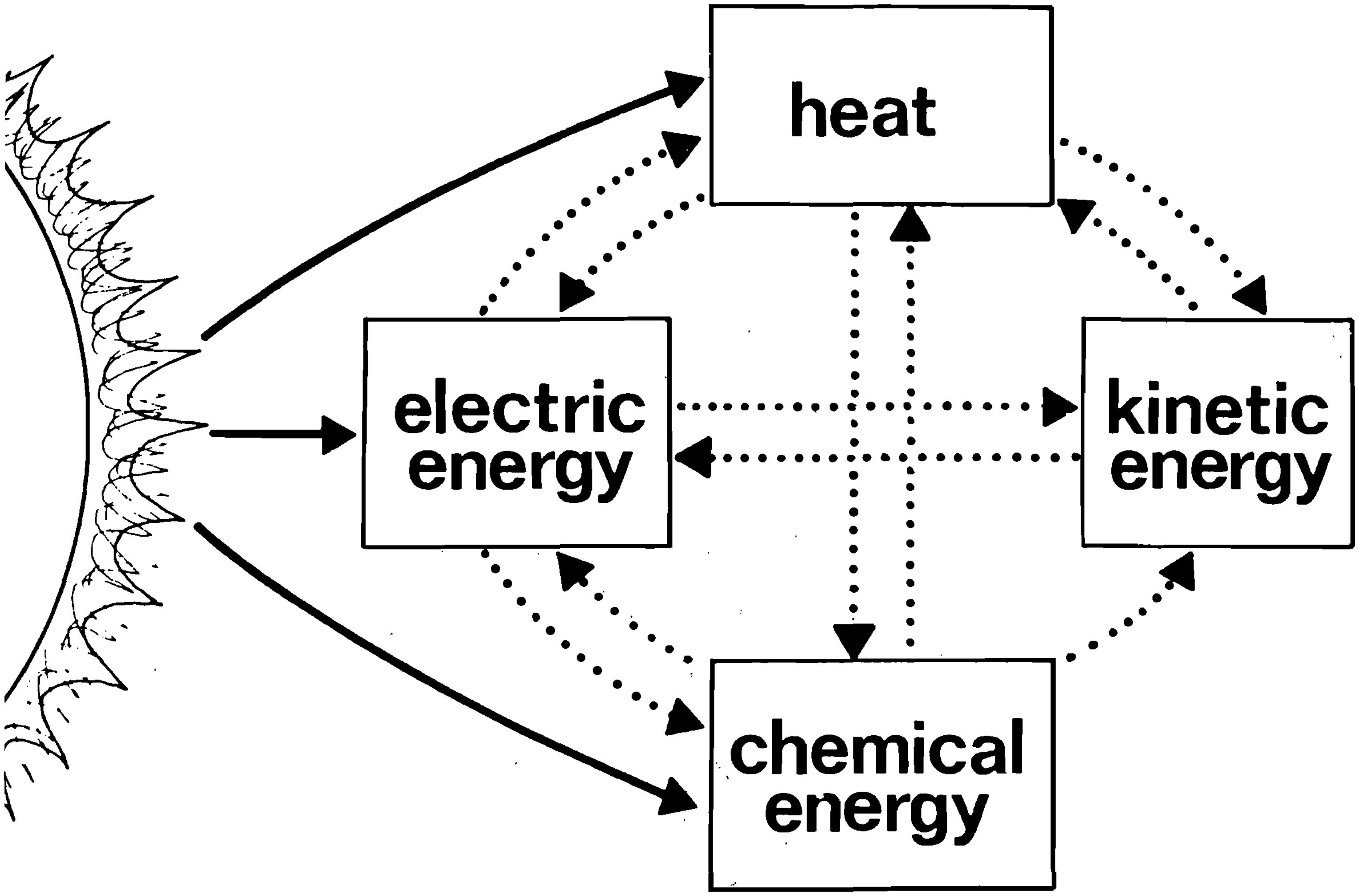
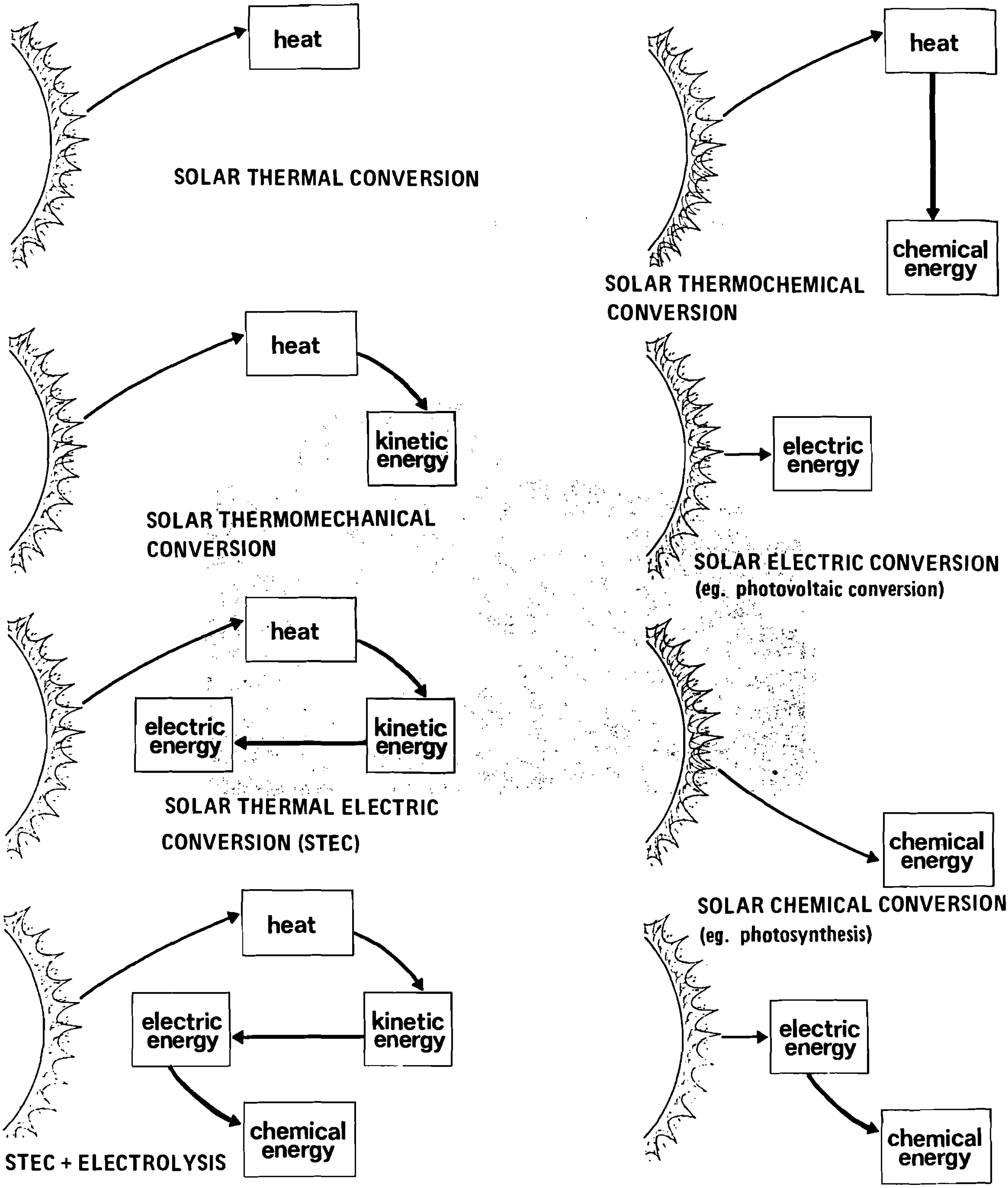


Figure 12



SOME THERMODYNAMIC CLASSES OF SOLAR ENERGY CONVERSION

Figure 13

COLORADO STATE UNIVERSITY SOLAR HEATED AND COOLED HOUSE (LABORATORY PROTOTYPE)

Figure 14

of commercial solar homes have been built or are under construction in the U.S., 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 (Olgyay, 1963) and energy efficient heating and cooling systems are far more cost effective, often by a factor of 5 to 10, (Goldstein and Rosenfeld, 1976) 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 (Figure 15). Even retrofitting of residential buildings is substantially cheaper (Table 12) than providing additional energy, whether by solar (Schulze, 1977) 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 (Schoen and Weingart, 1975) which has succeeded in a few European countries but which is unlikely to be an option in the United States for many decades (Bender, 1973). Today there are few places where active solar heating is competitive; in central Europe the effective cost of solar heating is between $ 5,000 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 between 50 and 70 percent of total annual heating demand (itself only 30 percent or so of total energy demand), the ultimate displacement of other primary energy forms by solar heating would be $(0.5)\times(0.50)\times(0.5 - 0.7) \times (0.3) = 3$ to 4 percent. 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.

<u>Solar Thermal Hydrogen</u>

In principle, hydrogen can be produced at potentially interesting costs from solar (and nuclear) generated high temperature heat (600 to 2500 deg. C), although a thermochemical hydrogen production process amenable to large scale commercial use has

RESIDENTIAL ENERGY USE IN EUROPE AND THE UNITED STATES

	DWELLING TYPE	THERMAL LOSS kW(th)-h/year	SYSTEM * EFFICIENCY	FUEL DEMAND kW(th)-h/year
UNITED STATES	SFD	25,600	0.63	40,000
	MFD	16,900	0.63	26,800
FRG	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

Source: WAES (1977)

* System efficiency is for fossil fuel conversion in the home. Efficiency of electric heat is considered 1.00 at end use; overall efficiency is approximately 0.33.

NOTE: SFD means "single family dwelling"; MFD means "multiple family dwelling"

Table 10

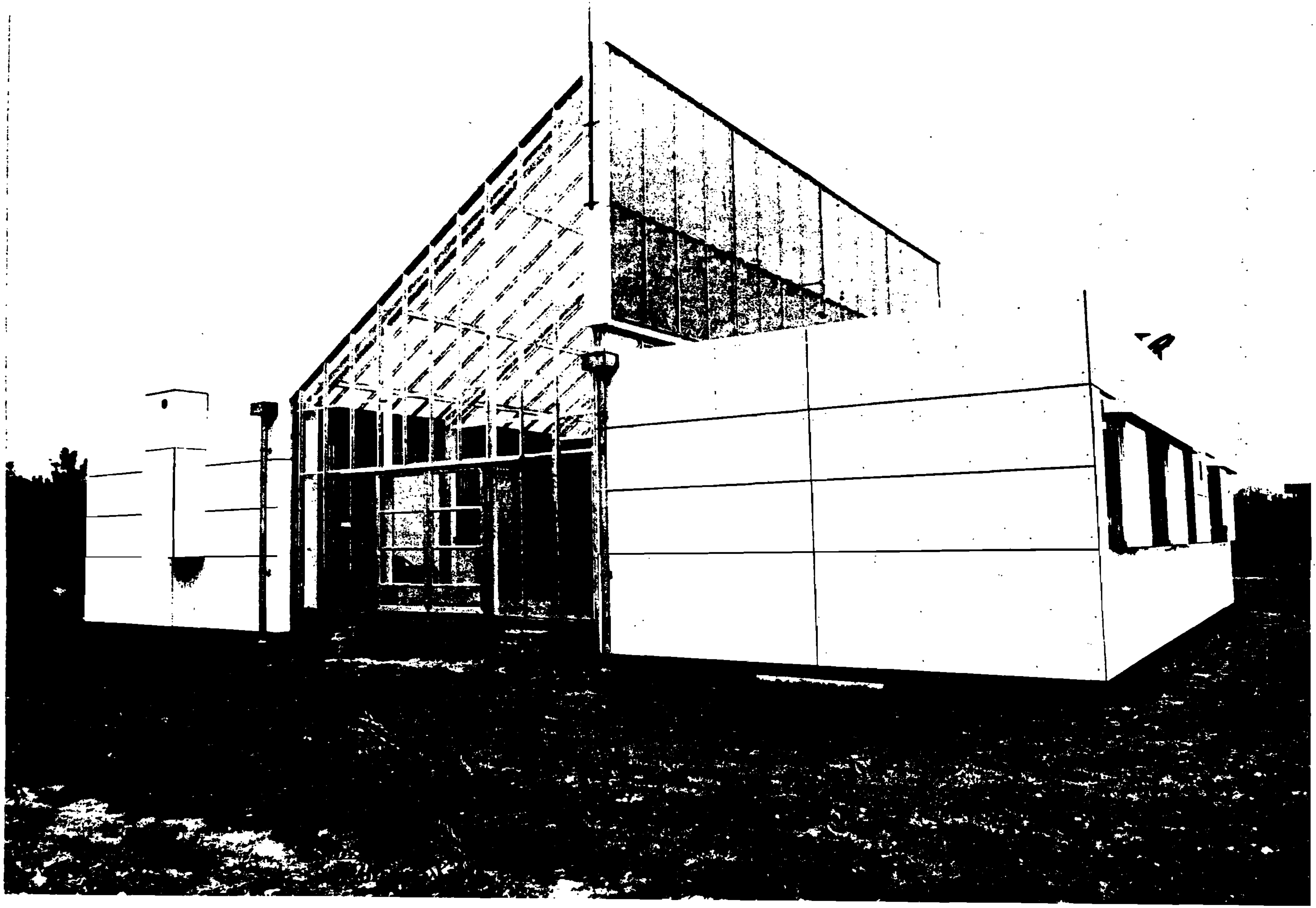
ANNUAL DEMAND FOR HEAT AND FUEL FOR VARIOUS HOUSES

BUILDING TYPE	THERMAL DEMAND *	FUEL DEMAND *
AVERAGE U.S. HOUSE	28,600	44,000
NEW HOUSE WITH PRESENT INSULATION PRACTISE	12,600 - 18,900	20,000 - 30,000
EASILY ACHIEVABLE WITH COST-EFFECTIVE INSULATION PRACTISE	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

* kW(th)-hours per year, system efficiency = 0.63 (fuel to useful heat)

Source: WAES (1977), Rosenfeld and Hollowell (1977), Sørenson, (1976)

Table 11



THE "ZERO ENERGY HOUSE" (DENMARK) - A PROTOTYPICAL LIVING SYSTEM WHICH REQUIRES NO EXTERNAL ENERGY FOR HEATING AND COOLING (Photograph by author)

Figure 15

ENERGY CONSERVATION MEASURES - COSTS AND ENERGY SAVINGS IN A TYPICAL U.S. HOUSE *

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	.011	3.2	0.75
INSTALL R19 CEILING INSULATION	19,400	921	.011	3.1	0.63
NIGHT SETBACK IN THERMOSTAT TO 16 C	16,400	0	0	0	0.53

* 135 m^2 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 percent load factor
EQUIVALENT COST OF DISPLACED ENERGY	$ .006/kWh(th) = $ 7.30/bbl heating oil combusted at 70% efficiency

Ref: Rosenfeld and Kukulka (1977)

Table 12

SOLAR SPACE HEATING:

AN ECONOMIC EXAMPLE FOR CENTRAL EUROPE

SOLAR SYSTEM COST[1] ($/m² collector)	$250/m²
Average insolation[2]	3-4 kWh/m² - day
Annual net utilization[3]	0.20 - 0.35
Percent total heat requirement supplied by solar[4]	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[5]	
$/kWh(th)	.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.

---

1 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.

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

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

4 Higher percentages supplied by solar heat correspond to lower total system heat utilization factors.

5 Actual fixed charge rates will be typically in the range of 10% to 20%; hence, the solar heat costs derived here are conservatively low.

Table 13

yet to be developed. However, over 10,000 possible therodynamic cycles have been identified and the efficiency of conversion from heat to hydrogen will be in the range of 30 to 90 percent (Gregory, 1976), depending in part on the temperature of the reaction (from 550 to 2000 deg. C). Advanced high temperature reactors produce heat at 1000 deg. C.; the reactor for the now abandoned U.S. nuclear rocket program operated at 2500 deg. 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 (1976) has carried out an extensive study of one process which 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 percent. Farbman estimates that a commercial prototype pilot plant could be operational in less than a decade, with development costs below $ 100 million. By comparison (Table 14), development costs (Caputo, 1977) 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 <u>aggressively</u> 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.) Though this may seem excessive; it is important to realize that the present prices (before taxes) of refined petroleum-based fuels such as gasoline are <u>already</u> on the order of $ 20 per barrel.

<u>Synthetic Liquid Fuels</u>

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 (1977b) has proposed increasing by sixfold the efficiency with which the carbon atoms in fossil fuels (especially coal) are used by combining 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 (Steinberg and Baron, 1977) indicates that such a process operating at high efficiency is technically feasible and may be economically attractive.

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 ~~4.0~~ (FRG) 10.0 (USA)
HIGH TEMPERATURE GAS COOLED REACTOR	1984	1.5
CENTRAL RECEIVER SOLAR ELECTRIC	1990	1.0

Table 14

COST ESTIMATES FOR PRODUCTION OF HIGH TEMPERATURE HEAT (> 600°C) BY SOLAR CENTRAL RECEIVER SYSTEMS

$/kW(th)*	REFERENCE
2050	JET PROPULSION LABORATORY (1975)
1500	McDONNELL (1975)
1840	MARTIN (1975)
1700	BLACK & VEATCH (1977)
1170	SMITH (1976)
1653 ± 333	

*Adjusted to 100% load factor

Table 15

A ROUGH ESTIMATE -- ECONOMICS OF SOLAR THERMOCHEMICAL HYDROGEN PRODUCTION

SUBSYSTEM	\$/kW(th)*
SOLAR THERMAL	1650 ± 300
THERMAL HYDROGEN	600 ± 400
	2250 ± 350

*At 100% effective load factor, FCR = 0.10
\$2250 ± 350/kW(H_2) \$44 ± 7/"bbl"

GASOLINE WITHOUT TAXES \$20 to \$40/bbl

Table 16

Solar Thermal Electricity

Direct beam sunlight can be converted to electricity at high efficiency (18 to 25 percent) 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 five years ago. Already a variety of small systems in the 1 to 100 kilowatt range are commercially available. Technologies which will lead to solar power plants as large as several hundred MW(e) are already well under development in the USA, Europe and Japan. A 400 kW(th) prototype is in operation in Georgia (USA), 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 1990's. (Table 17)

No approach has emerged as clearly superior, but present emphasis for large plants is on the "central receiver" system (Figure 16). In this design (Figure 17), direct sunlight is reflected (Figure 18) 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 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 square meters, and a central tower approximately 260 meters in height. To avoid shading and blocking of adjacent heliostats, the 0.5 sq. km of total reflecting surface plus the tower and associated facilities would occupy a region of approximately 1.2 square kilometers. Net conversion efficiency for these plants will be in the range of 17 to 25 percent (Figure 19).

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, 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 associated with high intensity solar radiation absorbers operating under rapidly changing high temperature conditions are being solved, and for the heliostats and thermal storage

CONSTRUCTED, PLANNED OR CONTEMPLATED CENTRAL RECEIVER AND DISTRIBUTED SOLAR THERMAL ELECTRIC FACILITIES

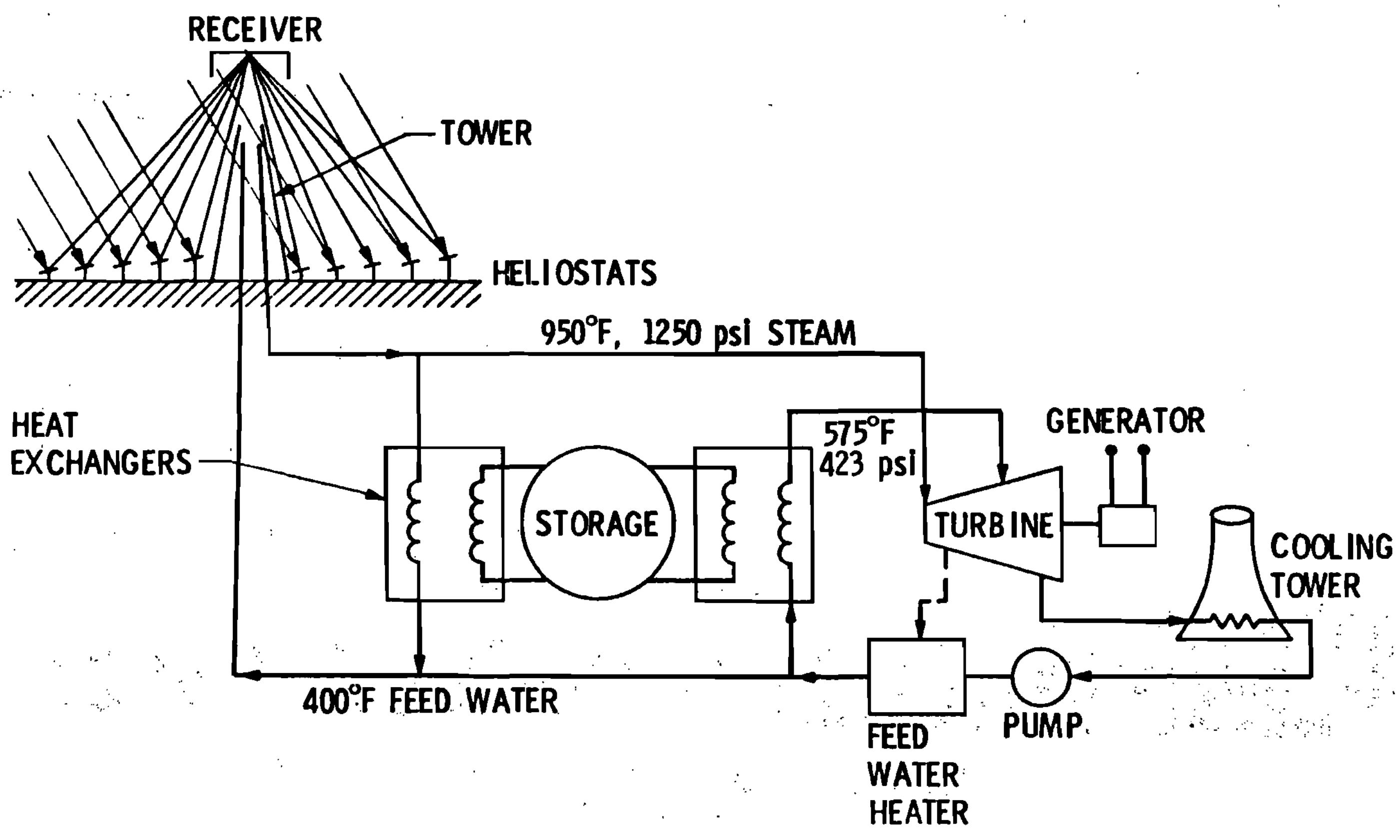
FACILITY	LOCATION	CAPACITY	COMPLETION	SPONSORS
Solar furnace	Odeillo, France	1 MW(th)	1969	CNRS
Solar thermal test facility	Albuquerque, New Mexico (USA)	5 MW(th)	1978	ERDA
Central receiver (steam cycle)	Genoa, Italy	0.1 MW(e)	mid 1960's	Prof. Francia
Solar thermal central receiver test facility	Georgia Institute of Technology, Atlanta, Georgia (USA)	0.4 MW(th)	1977	ERDA
Central receiver, steam cycle	Southern France	5 MW(e) *	1982 *	CNRS
Central receiver, steam cycle	Barstow, California (USA)	10 MW(e)	1982	ERDA, SCE, LADWP
Distributed system, steam cycle	(to be determined)	10 MW(e)	1982 *	ERDA
Central receiver, steam cycle	Southwest USA	100 MW(e)	1985 *	ERDA
Distributed system, steam cycle	Southwest USA	100 MW(e)	1985 *	ERDA
Central receiver gas turbine hybrid with fossil fuel backup	Southwest USA	2 MW(e)	1981 *	EPRI
Central receiver	Spain	10 MW(e)	mid 1980's	European Community

* Approximate

CNRS = Centre National de la Recherche Scientifique (France)
ERDA = Energy Research and Development Administration (USA)
SCE = Southern California Edison Company (USA)
LADWP = Los Angeles Department of Water and Power (USA)
EPRI = Electric Power Research Institute (USA)

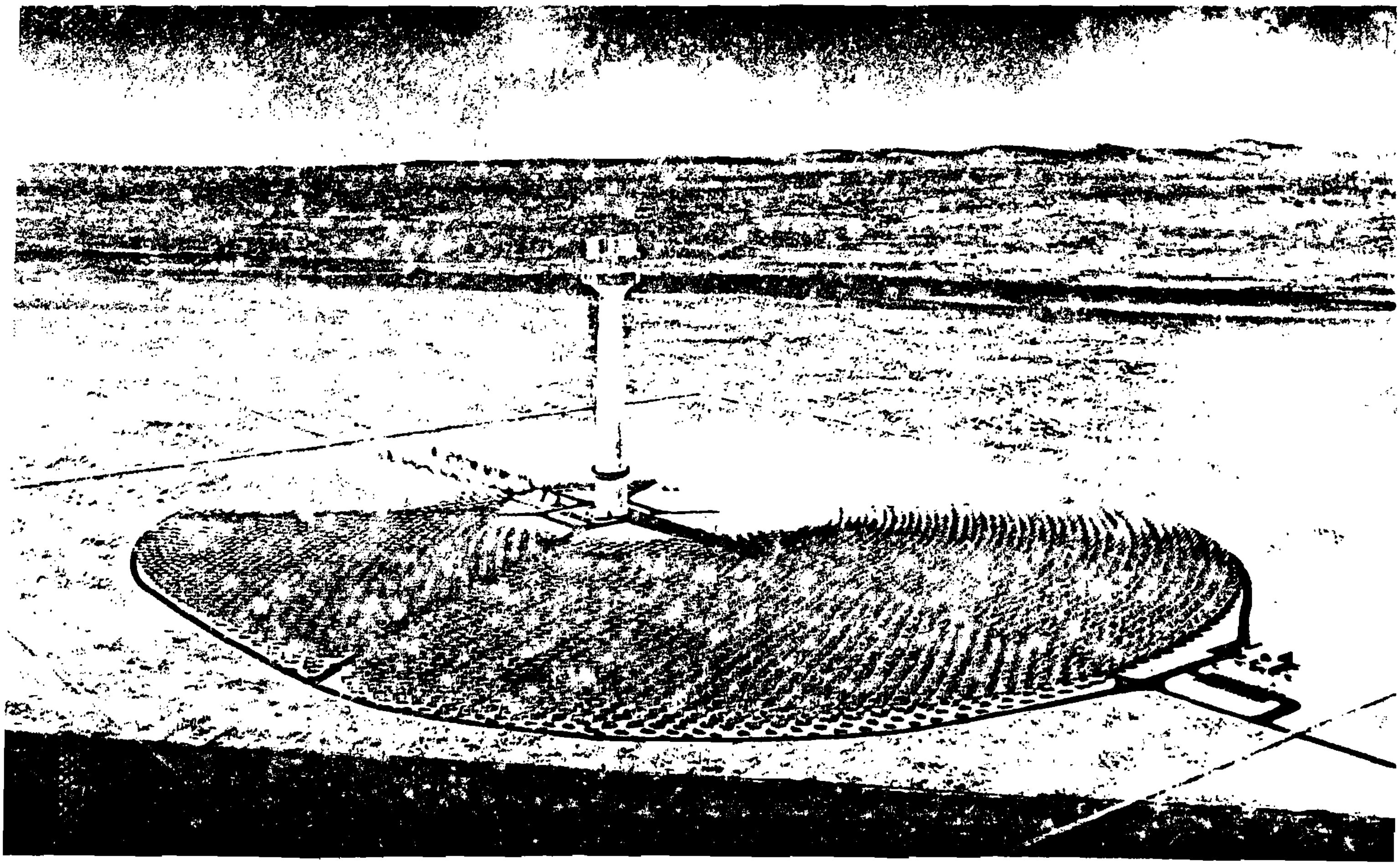
Table 17

CENTRAL RECEIVER
SOLAR THERMAL-ELECTRIC POWER PLANT



Ref: Caputo, 1977 Courtesy NASA/JPL

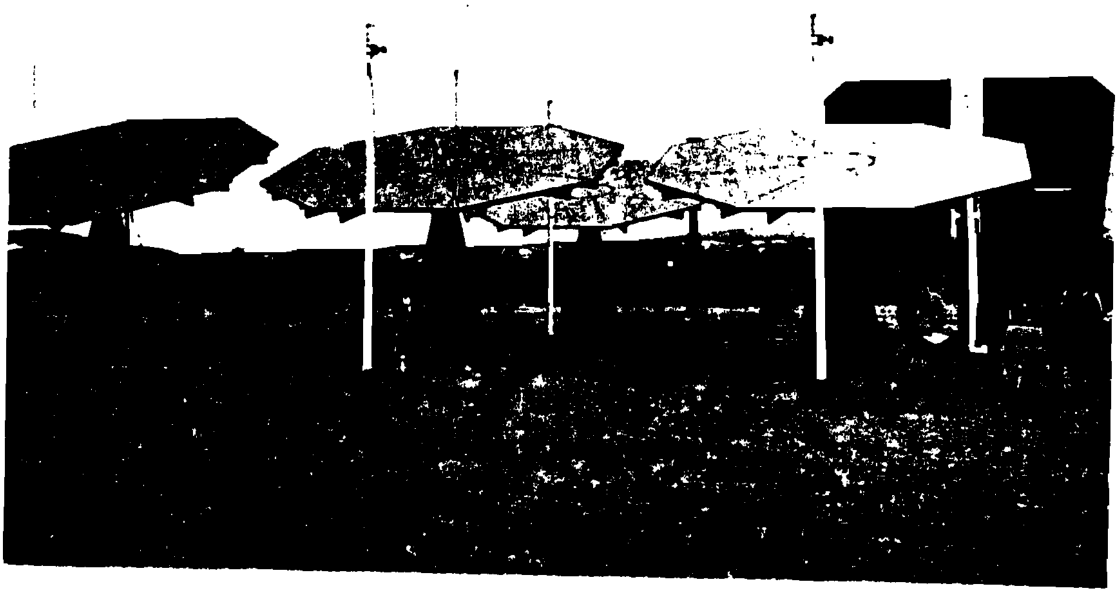
Figure 16



60 MWe OPEN CYCLE GAS TURBINE SOLAR ELECTRIC PLANT
ELECTRIC POWER RESEARCH INSTITUTE
BLACK & VEATCH · DESIGN ENGINEER

Figure 17

PROTOTYPE HELIOSTATS FOR LARGE SCALE SOLAR POWER PLANTS (McDonnell-Douglas Design)

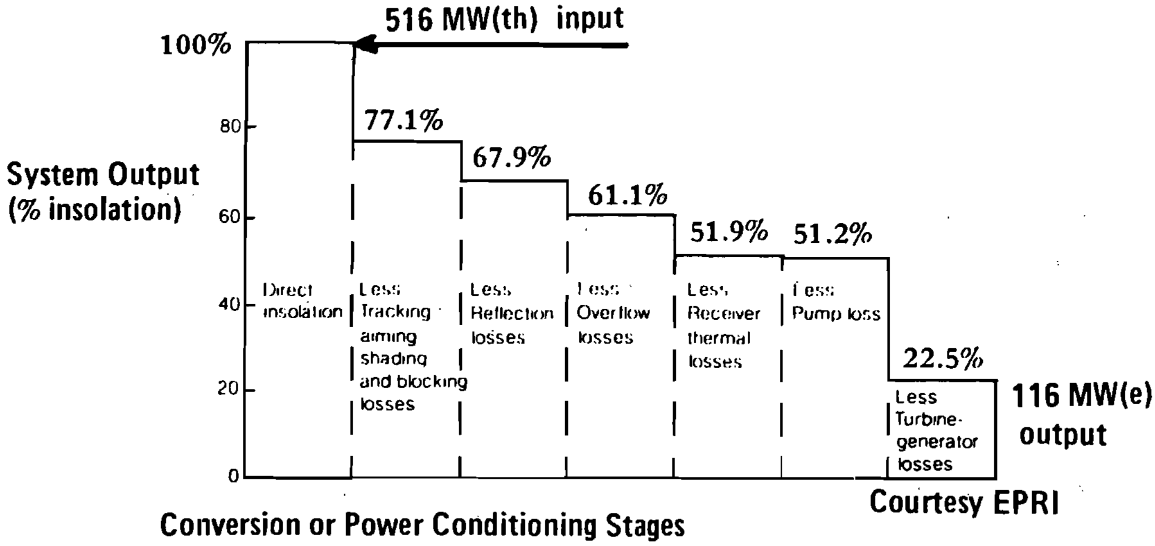


Courtesy Sandia Livermore

Figure 18

CALCULATED PERFORMANCE * OF A CLOSED BRAYTON CYCLE (HELIUM) SOLAR THERMAL ELECTRIC POWER PLANT

* Calculated at summer solstice for Inyokern, California (USA)



Courtesy EPRI

Reference: Gintz, J. et al. (1976). "Closed Cycle, High Temperature Central Receiver Concept for Solar Electric Power" EPRI No. ER183

Figure 19

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)-h (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 continue 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 <u>optimum arid sunny regions</u> exceeds long distance HVDC transport costs by a factor of 10 (Table 20).

<u>Photovoltaics</u>

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 (Figure 19a) of other semiconductor materials, conversion efficiencies of 10 percent to over 20 percent 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 (Figure 20) 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 LDC's 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 <u>millenia</u>, not decades. New techniques to assure

STEC TOTAL COST ESTIMATES

$/kW(e)*	REFERENCE
2700	JPL (1975)
2100	McDONNEL (1975)
2700	MARTIN (1975)
2260	BLACK & VEATCH (1975)
1610	O. SMITH (1976)
2274 ± 456	

*load factor = 0.5; $77; direct costs x 1.5 = total costs, central receiver system

Table 18

COST COMPONENT **	JPL (1)	McD (2)	Martin (3)	B & V/ EPRI (4)	B & V/ EPRI (5)	SMITH (6)	CSU (7)	ANSALDO MBB (8)	JPL (9)
LAND & SITE PREPARATION	10	32	115	27	10	11	33	--	6.5
STRUCTURES & FACILITIES	--			110	--	--	--	3300	---
HELIOSTATS & 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 & 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) (year estimated)	2320 (75)	1815 (75)	2325 (75)	4794 (75)	1950 (75)	1494 (76)	770 (73)	8190 (76)	3156 (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 (Hrs)	4.2	4	---	6	Weeks	6	2	0	4.2

ESTIMATED COST COMPONENTS FOR RECENT CENTRAL RECEIVER STEC POWER PLANT DESIGNS

** All costs in $/kW(e)$_{rated}$

Table 19

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) 200 – 300 (CENTRAL EUROPE)

Table 20

PROTOTYPE THIN FILM CADMIUM SULFIDE

SOLAR CELL UNIT

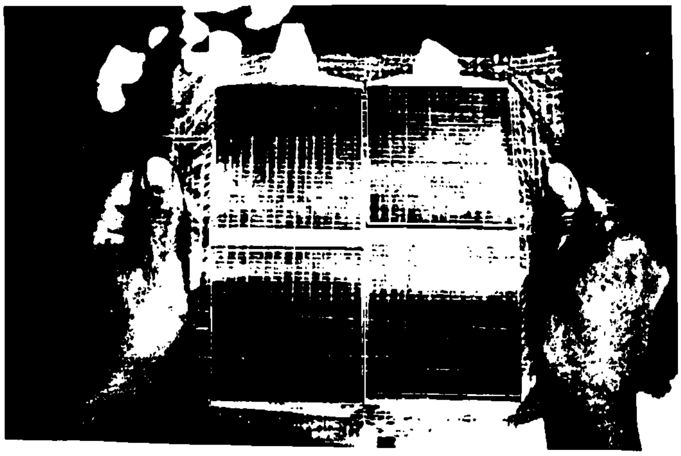


Figure 19a

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 21

SPACE TECHNOLOGY IN THE DEVELOPING WORLD - SOLAR CELL POWERED EDUCATIONAL TELEVISION IN A VILLAGE SCHOOL ROOM IN NIGER

Figure 20

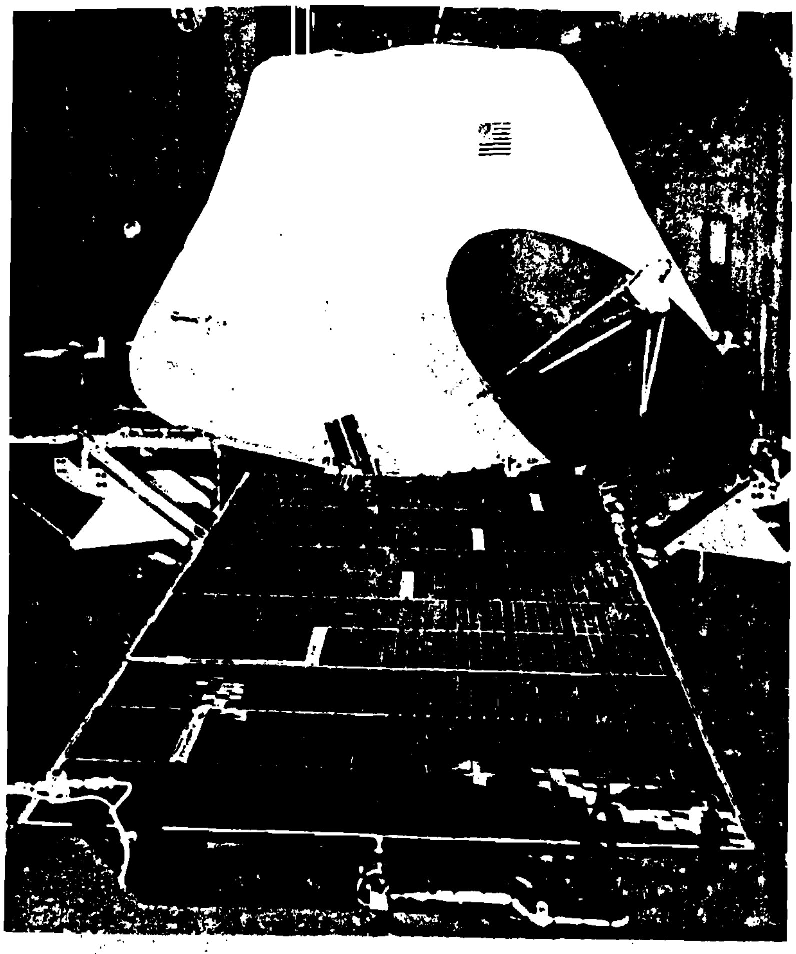
effective sealing, such as integration of the silicon with a glass cover (already experimentally demonstrated) and protection against corrosion of metallic conductors must be commercially developed. Large scale production may be similar to the present production of very complex multilayer planar structures - 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 would come the extraordinary possibility of giving to tens and possibly hundreds of human generations a true energy dowery. 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 (Figure 21). 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 to $ 25,000 per average kW(e). Further reduction to $ 2000 per peak kW(e) is expected within a few years, and the U.S. Dept. of Energy is aiming for $ 500 per peak 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. (Figure 22). The eventual price of complete photovoltaic arrays is estimated to lie in the range of $ 400 - $ 600 per peak kW(e) or $ 1,200 - $ 1,300 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 to $ 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 lightweight, but highly rigid space frames; here perhaps the possibility is for costs below $ 1,000 per average kW(e).

Recent advances in electrochemistry (Manassen et al, 1977) 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

SILICON PHOTOVOLTAIC ARRAY FOR THE MARINER 9 SPACECRAFT



Courtesy Jet Propulsion Laboratory

Figure 21

CONTINUOUS GROWTH OF HIGH QUALITY SINGLE CRYSTAL SILICON RIBBON BY THE EFG PROCESS

Courtesy Mobil-Tyco Solar Energy Corp.

Figure 22

ESTIMATED PHOTOVOLTAIC ARRAY SUBSYSTEM COSTS[1]

OPTICAL CONCENTRATION	ARRAY CONVERSION EFFICIENCY	TRACKING CAPABILITY	$\$/m^2$ ARRAY	$\$/m^2$ CELL	$\$/m^2$ STRUCTURE	$\$/kW(e)_{AVERAGE}$[3]
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[2]		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		2000	150	5300
40 - 90	0.12	2 AXIS TRACKING		2000	75	3000
60 - 150	0.15	2 AXIS TRACKING		2000	50	1600
300 - 600	0.18	2 AXIS TRACKING		20,000	75	2000

<u>NOTE</u> $\$2000/kW(e)_{average}$ at 0.10 fixed charge rate $ 0.023/kWh(e)

1 Sandia (1976). System assumed to operate in Albuquerque, New Mexico (USA).

2 "CPC" - Compound Parabolic Concentrator (Winston, 1976).

3 U.S. dollars, late 1975

Table 22

required in association with photovoltaic conversion for any commercial electric applications.

Bioconversion

Poole (1977) 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 (Lonnroth, 1977), and Brazil has embarked on an ambitious program to produce methanol from sugar cane to displace gasoline for transportation.

Photosynthetically produced sugar and starch and hydrocarbons (Calvin; 1976a, 1976b) 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 to 3 percent for such species as water hyacinth, sugar cane, and fresh water algaes (Table 23). Subsequent conversion to useful high quality fuels further lowers overall efficiency to 1 to 2 percent. 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 (about 20 deg. 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 deg. of latitude. A "practical" upper limit of 1 to 10 TW(th) has been assumed here, with environmental and climatic impacts assumed to be limiting factors. However, this is only a rough 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

BIOMASS ENERGY YIELDS OF SELECTED PLANT SPECIES

SPECIES	t/ha–yr	10^8 kJ/ha–yr	W(th)/m^2	CONVERSION EFFICIENCY (%)*
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 Inman, 1974

*Average insolation of 5 kWh/m^2–day = 210 W/m^2

Table 23

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 (1975) and Lockheed (1975), 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 percent 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, liquifaction and cryotanker transport could be over one hundred dollars per "barrel" equivalent of oil (Table 25).

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 uncertanties 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 (Gerlach, 1977).

Requirements for land (and perhaps ocean) areas will be extensive. (Table 26) However, considering that almost 10 percent of the world's land mass is under cultivation and another 14 percent is partially used pasture, it seems reasonable to consider conversion of 1 percent of arid, nonproductive regions to solar energy "farming". (1 percent corresponds to 50 TW(th) to 100 TW(th) primary energy conversion). Depending on the classification chosen (Figure 23), the arid regions of the world, including the deserts, comprise between 22 and 30 million square kilometers of land, or roughly 15 to 20 percent 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 percent of the land (Table 27), compared with the 41 percent already committed to crops and grassland pasture. (For comparison, roads cover 1 percent 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 percent of the land and on 3 percent of the land in the German Federal Republic (Table 28). Economic considerations rather than

ESTIMATED CAPITAL COSTS FOR OTEC PLANTS

DESIGNER	COSTS IN \$/kW(e)		
	DIRECT	INDIRECT*	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 MISSLES & SPACE	3057	1530	4590
BLACK & VEATCH	2560	1280	3840

AVERAGE = \$3622 + \$670 (1 S.D.)

* 50% OF DIRECT

Table 24

COSTS FOR PRODUCTION AND LIQUEFACTION OF HYDROGEN BY OTEC PLANTS USING ELECTROLYSIS

PROCESS	H_2 COSTS (\$ / bbl)
ELECTRICITY FROM OTEC (1) & H_2 BY ELECTROLYSIS (2)	45 - 180 12
LIQUEFACTION OF H_2	25 - 75
6000 km CRYOTANKER TRANSPORT	3 - 8
LANDED COST	85 – 275

(1) \$ ~~3000~~ 2000/kW(e), 0.9 LF, 0.10 FCR = \$ 45/bbl
\$ ~~2000~~ 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

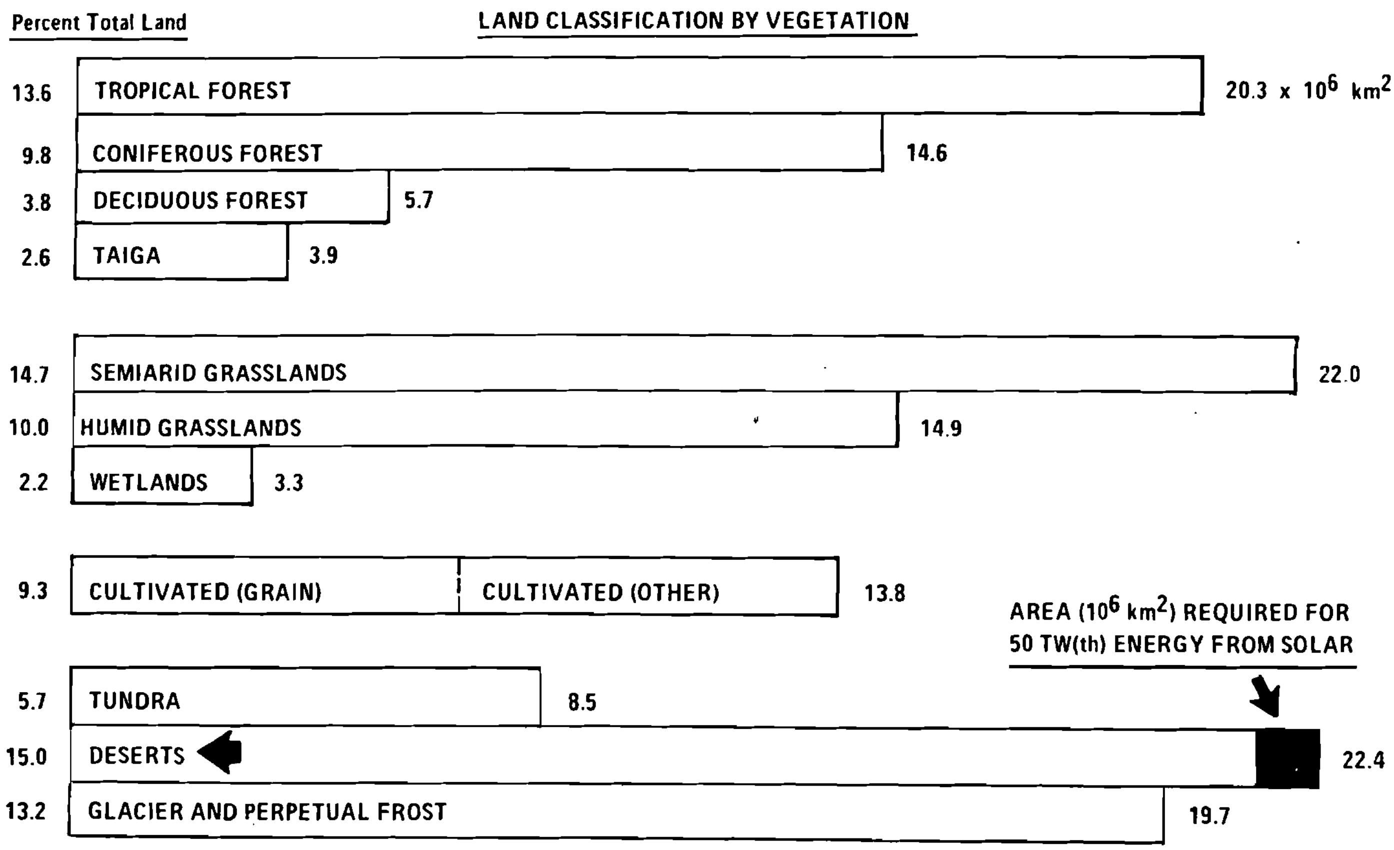
Table 25

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, 1974;

Table 26



Reference: Deevey, E. The Human Population, Scientific American, Sept.1960

Figure 23

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*	.012	0.2	55
SOLAR FUELS•	.038	0.64	170
TOTAL SOLAR FOR PRESENT ENERGY DEMAND	.05	0.84	225

*1 kW(e)/capita average end use rate, net efficiency = 0.10 over dedicated land

•solar fuel production 50 W(th)/m^2 land

Table 27

SOLAR ENERGY CONVERSION & LAND AREA REQUIREMENTS IN EUROPE

	FRG	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* (non-electric uses) in $10^3 km^2$ (% of total land)	8.44 (3.4%)	5.84 (1.1%)	3.35 (1.1%)
Solar Land* (electricity)	1.16 (0.5%)	0.68 (0.1%)	0.62 (0.2%)

* Assumes average insolation of 3.0 kwh/m^2 -day, conversion efficiency = 20% for solar-derived energy

Table 28

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 20 percent 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, though 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 kW nor in the efficiency of materials production, the direct energy payback time for STEC and solar thermal hydrogen units located in high insolation environments is six 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 (Caputo , 1977). Conventional silicon solar cells, by contrast, would require roughly 20 years to repay the energy consumed in their production, but detailed calculations (Mlavsky, 1976) 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 (Perry et al., 1977; Weingart and Laitone, 1978).

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 (Budnitz and Holdren, 1976). Davidson and Grether (1977) 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 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

NET ENERGY ANALYSIS FOR McDONNEL 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 29

MATERIALS REQUIREMENTS FOR FISSION AND SOLAR POWER PLANTS**

MATERIAL	1100 Mwe LWR[4]	STEC[1]	R_1	R_2
CONCRETE	483	456	0.94	2.8
STEEL	15 (2)	121 (3)	8.00	24.0
REBAR	11	5	0.45	1.3
GLASS	---	77		

(1) MacDonnel Douglas 15 Mw(e) Solar Thermal Electric Plant.

(2) Stainless steels.

(3) Low carbon steel.

(4) Data from Bechtel Corporation.

R_1 = Solar to nuclear materials ratio based on nameplate capacity.

R_2 = Solar to nuclear materials ratio adjusted for 0.8 load factor for MacDonnel STEC design. STEC includes only heliostat materials.

** (kg/kw_e)

Table 30

MATERIALS REQUIREMENTS TO CONSTRUCT

TEN Gw(e) STEC PLANTS PER YEAR

Material	(a) mtons/year(STEC)	(b) USA Production	(a)/(b)
STEEL	1.44×10^6	1.4×10^8	.01
CEMENT	4.56×10^6	9.0×10^7	.05
SAND, GRAVEL	12.0×10^6	9.5×10^8	.01
GLASS	$.77 \times 10^6$	1.2×10^7	.06

NOTE: Materials requirements for 15 Mw(e) MacDonnell-Douglas design. U.S. production in mtons/year. Cement + sand + gravel = concrete. U.S. Production for 1973.

Table 31

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

Table 32

valleys to provide pumped hydrostorage units, and the aesthetic 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 (Figure 24) both the boundary conditions and energetics of the climatic system (Weingart, 1977b). Surface albedo (Figure 25) and surface roughness will be altered, as will surface hydrology in non-arid regions. Solar radiation may be converted to latent heat through evaporative cooling (especially for solar electric facilities located in coastal desert regions.) OTEC 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 (Williams et al, 1977) 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 (Baes et al., 1976; Schneider, 1977) that the increasing atmospheric carbon dioxide levels associated with fossil fuel combustin 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 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 Figure 26. 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 industrialized world demonstrates that four to five decades are required before new energy technologies can command a substantial fraction (30 to 50 percent) of total primary energy use. While 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 (1973), following the discovery of Fisher and Pry (1971) that many competitive market substitutions are logistic, has found that the energy marketplace of most industrialized

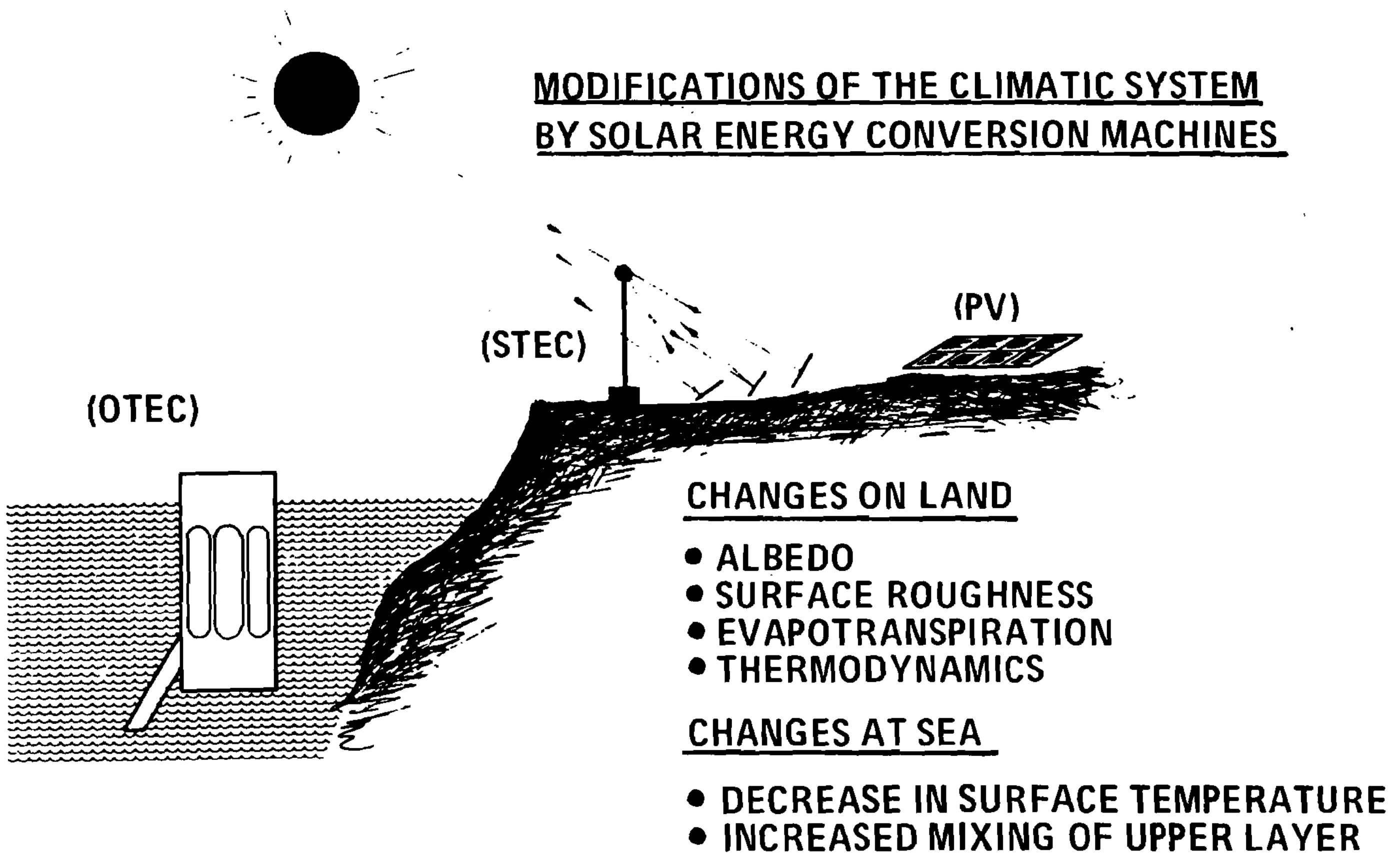
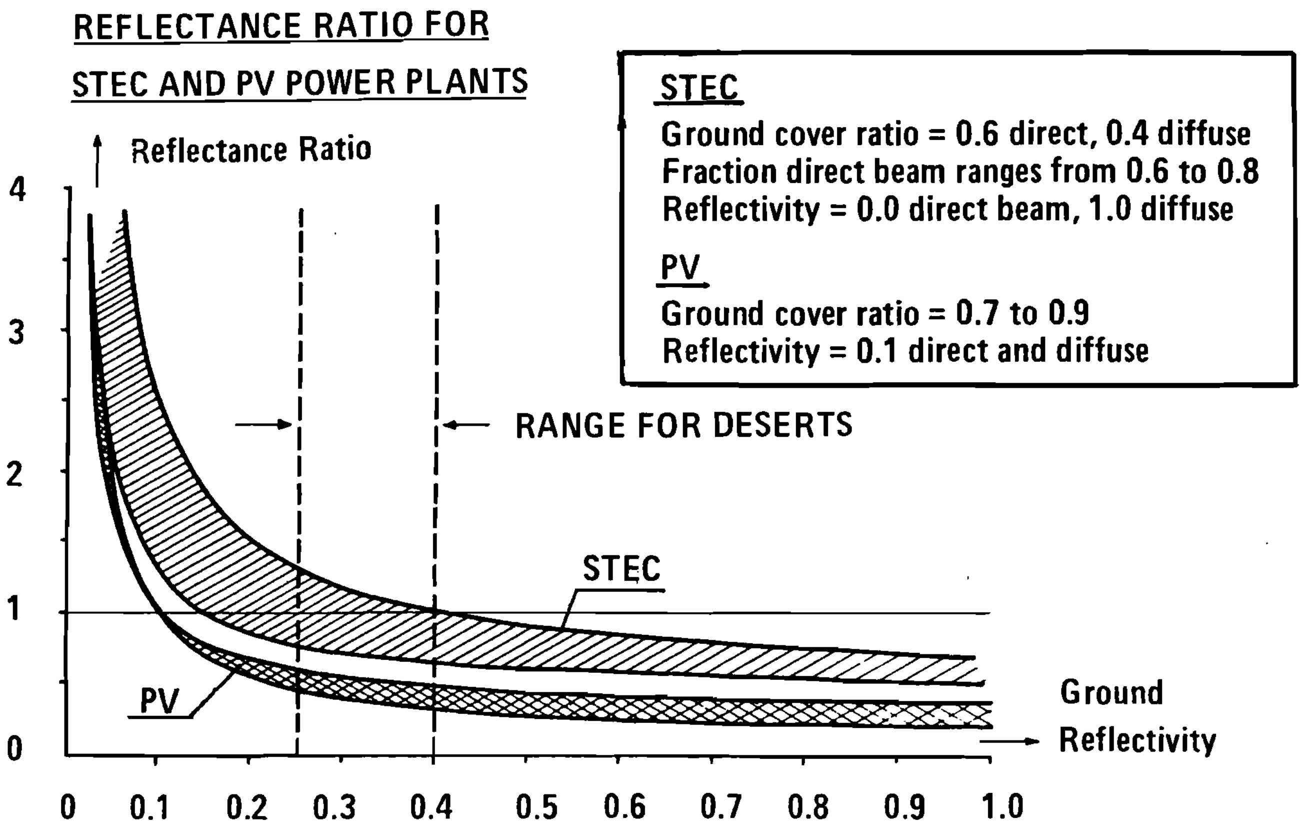

MODIFICATIONS OF THE CLIMATIC SYSTEM
BY SOLAR ENERGY CONVERSION MACHINES
(STEC)
(PV)
(OTEC)
CHANGES ON LAND
• ALBEDO
• SURFACE ROUGHNESS
• EVAPOTRANSPIRATION
• THERMODYNAMICS
CHANGES AT SEA
• DECREASE IN SURFACE TEMPERATURE
• INCREASED MIXING OF UPPER LAYER

Figure 24



REFLECTANCE RATIO FOR
STEC AND PV POWER PLANTS
Reflectance Ratio
STEC
Ground cover ratio = 0.6 direct, 0.4 diffuse
Fraction direct beam ranges from 0.6 to 0.8
Reflectivity = 0.0 direct beam, 1.0 diffuse
PV
Ground cover ratio = 0.7 to 0.9
Reflectivity = 0.1 direct and diffuse
RANGE FOR DESERTS
STEC
PV
Ground
Reflectivity
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 25

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 which differ for the various primary energy sources and for the period of concern (entry or exit).

This remarkable behavior is shown in Figure 27 for the United States and in Figure 28 for the world. The multi-decade 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 percent of U.S. energy needs by 1985 and that subsequent energy market penetration could procede 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 percent of national energy use. On the global scale, assuming 1 percent 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 percent 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 (Weingart and Nakicenovic, 1978) of virtually all available solar energy market penetration scenarios for the United States suggests that most current projections including federal goals for the year 2000 and 2020, are ahistorically optimistic (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 vey large scale over the coming century, may only be a transitional energy option on the way to a global solar economy.

SCENARIOS AND PROJECTIONS OF TOTAL ENERGY DEMAND AND THE SHARE POTENTIALLY AVAILABLE FROM SOLAR ENERGY (USA)

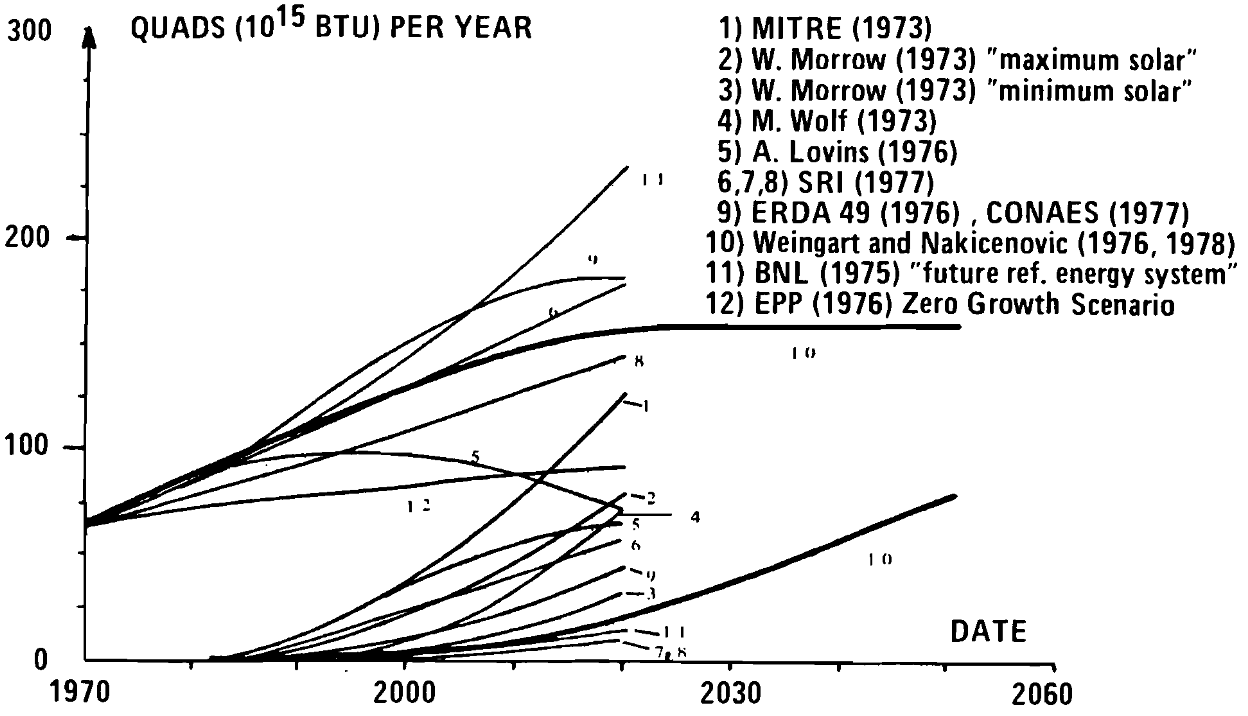
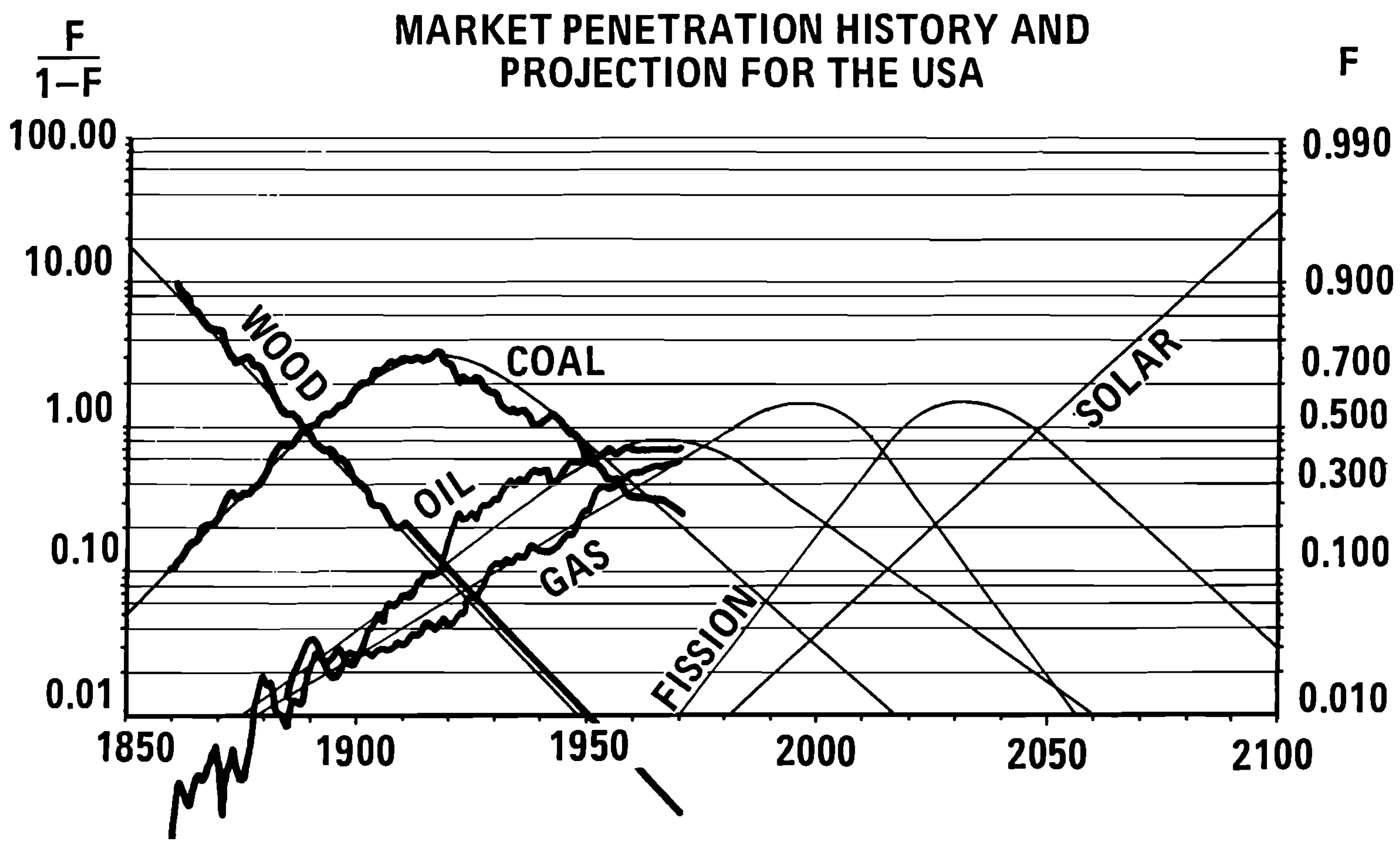
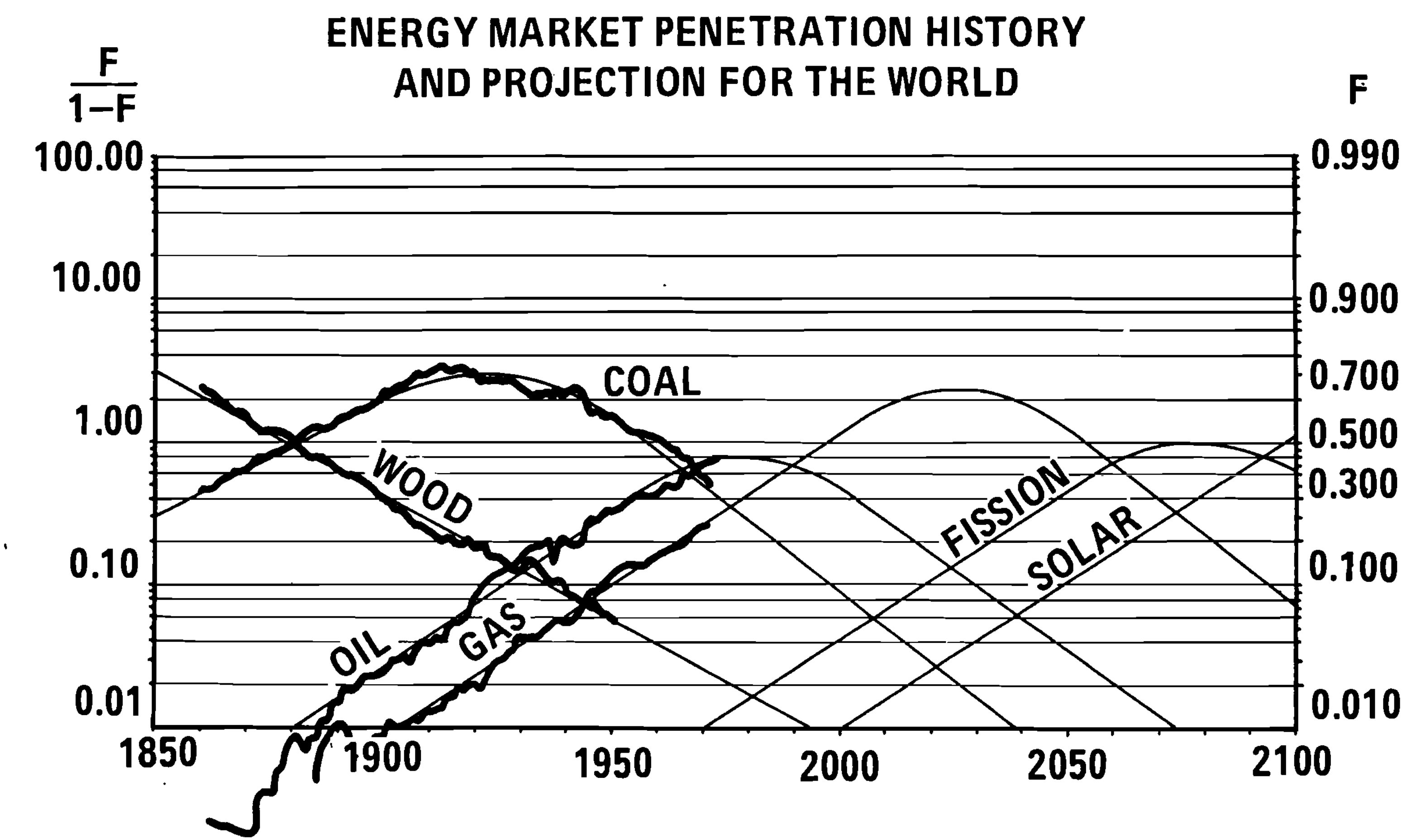


Figure 26



MARKET PENETRATION HISTORY AND
PROJECTION FOR THE USA
F/(1−F)
F
100.00
10.00
1.00
0.10
0.01
0.990
0.900
0.700
0.500
0.300
0.100
0.010
1850
1900
1950
2000
2050
2100
WOOD
COAL
OIL
GAS
FISSION
SOLAR

Figure 27



ENERGY MARKET PENETRATION HISTORY
AND PROJECTION FOR THE WORLD
F/1−F
100.00
10.00
1.00
0.10
0.01
F
0.990
0.900
0.700
0.500
0.300
0.100
0.010
1850
1900
1950
2000
2050
2100
COAL
WOOD
OIL
GAS
FISSION
SOLAR

Figure 28

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 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 which could lead to new possibilities for Mankind, to provide the metabolic basis for a stable, sustainable world.

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