SOLAR ENERGY FOR THE NEXT 5 BILLION YEARS

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ABSTRACT

This report attempts to stand back and look at our global energy system as a macrosystem. The past heroic energy substitutions researched by IIASA are used as a guide to the future. The major barriers to and potential of global solar energy for an increasingly industrialized society to the year 2100 are identified and evaluated.

Primary aspects considered are the resource magnitude, economic, macrosystem behavior, social, environmental, and health characteristics. These aspects reveal no basic obstacle to putting the global energy system on a solar basis within an appropriate transition time.

The outstanding unique characteristic of possible solar futures lies in the wide range of possible social characteristics, or what one might call "switch-hitting" ability of solar, which sharply sets it apart from long-range conventional options. Also, the interdependence it could foster between "North" and "South" nations is quite unique. Resource magnitude is potentially enormous (80 - 280 TWyr/yr), economic and macrosystem behavior looks reasonable, and environmental and health effects seem very attractive.

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INTRODUCTION

The use of solar energy to provide our global energy needs after the fossil fuel era is a technical possibility as realistic as the use of burner-breeder reactors. The magnitude of the resource is sufficient, and the technical expertise required to put this approach into practice is available, if not yet in a fully commercial form. However, these are necessary but not sufficient conditions for widespread societal use. The factors that will determine the magnitude of the future use of solar energy, its form, scale, ownership and institutional arrangements, as well as the rate of introduction, are factors that go well beyond engineering and economics. As in the past, these factors include the preferences of a society stimulated by technological development within a macrosystem context. The macrosystem is the aggregated behavior of the host of decision makers at all levels of society with regard to energy use.

It is the purpose of this paper to work through the above line of argument in detail. We start by presenting a plausible business-as-usual oil through natural gas to nuclear energy projection well beyond 2030. As will be seen, this is dominated through the latter half of the next century by fossil fuels, after which nuclear reactors come to constitute the bulk of the energy system. Solar technologies play only a minor role. We then pose the question, "In developing this projection have we perhaps neglected some factors that would drive the system towards incorporating a substantially larger role for solar?" Our answer is yes. For example, the range of values and preferences often expressed during debates on nuclear power indicates that it would be presumptuous to assume that there is now a social preference for nuclear development or that there will be a future preference. However, we do make the observation that constraints introduced by changing social preferences may lead to a future more favorable to solar development than that future assumed in the oil/natural gas/nuclear projection.

Once such a possibility is recognized, we must ask whether the solar technologies we can envision in fact have the potential to take a major role in the future global energy system. In this paper we examine possible resource constraints both for fuel (i.e., insolation requirements) and for materials; we examine possible constraints on our ability to streamline solar systems (e.g., constraints due to the intermittent nature of sunlight and storage requirements); we examine possible economic or cost constraints and also environmental constraints; and finally we come almost full circle and examine constraints that might arise owing to possible changes in social preferences, changes not unlike those that were mentioned above and the possibility of which prompted this whole examination of solar.

While some of the obstacles confronting major solar development are significant, the general conclusion that emerges from our examination is that there is certainly no "factual basis" for categorically dismissing now the consideration of a global energy system based eventually on solar rather than on nuclear technologies. Therefore, at the end of the paper we contrast with the oil/natural gas/nuclear projection, a range of projections in which solar is the principal, eventual contributor. Hopefully, a more comprehensive appreciation of the range of possible futures is provided by this analysis.

A PLAUSIBLE OIL/NATURAL GAS/NUCLEAR ENERGY PROJECTION

In order to consider the possibility of the future use of solar energy, there should be some attempt to understand the basis for past transitions. This should also give some insight into which energy systems are likely to exist prior to the entry of solar energy. This is important since it will determine the likely industry infrastructure and some cultural conditions that may exist, and define at least the initial climate for solar entry.

We have witnessed a limited number of subsitutions of one form of energy for another; in each case a substitution occurred even though the use of the original fuel was entrenched and pervasive throughout society. Consider the world market penetration dynamics as given in Figure 1, where the competition among primary energy sources is plotted on the logarithmic scale as a function of $F/(1-F)$, where F is the market share of a given technology. We see that historical penetration rates were rather slow and fairly regular for all primary energy sources. This phenomenological analysis of the past shows that each primary energy source has required about one century to increase its market share from 1% to 50%. These energy substitutions have occurred in some cases in spite of cost effectiveness (coal was cheaper per unit energy than the oil that displaced it over most of the time of substitution at the wholesale level) and in spite of plentiful resources (coal was in no danger of depletion while being displaced by a much more limited resource,

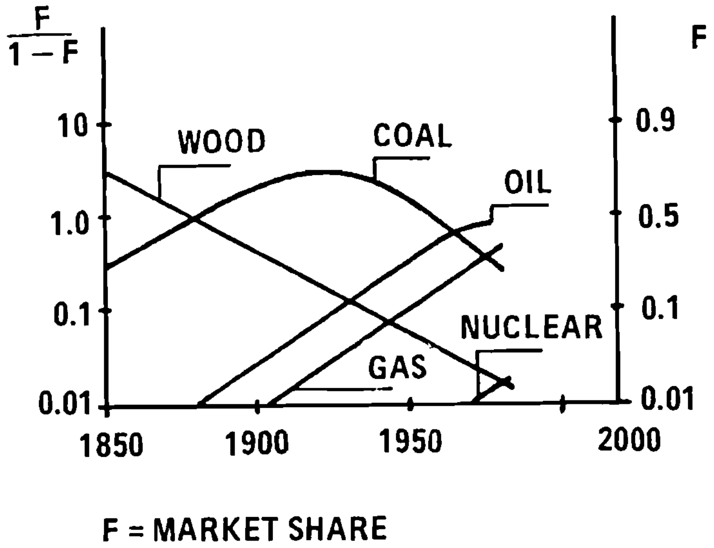

Figure 1. Evolution of world primary energy mix (Marchetti and Nakicenovic 1979).

oil). Similar statements apply for wood while it was being displaced by coal, although early use of coal seemed to be for its chemical properties rather than just its energy content. Probably, the next substitution of oil by natural gas will have its own counter-intuitive statements associated with its ascendency. These past substitutions seem to have more to do with system streamlining (i.e., system convenience or societal preferences) than anything else. Wood collection, transport, storage and end-use inconveniences increased as user load centers increased in size owing to continued industrialization and urbanization (Doxiadis and Papaioannou, 1974). So although we never utilized the up to 29 TWyr/yr of possible wood energy (Häfele, 1981*) (the world currently uses about 8 TWyr/yr of commercial primary energy), the somewhat more convenient coal gathering, transport, storage and end-use caused it to replace wood globally by 1900. In a similar fashion, the greater ease of oil gathering, transport, storage and end-use allowed it to replace coal by 1950 in the US and by 1965 on a global basis.

This streamlining seems to describe differences in fully mature systems with fully developed infrastructures. However it does not adequately explain why a new primary energy source starts to penetrate. Early market entry may have more to do with conditions and attitudes in the dominant and successful industry. The very success seems to leave the industry almost incapable of responding to new opportunities. This inflexibility might be considered as a kind of institutional old age. The massive industry looks formidable but lacks the ability to function the way it did in its youth. Thus it is susceptible to market penetration by a much smaller, adaptive, and dynamic organization.

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*See Energy Systems Program Group of the International Institute for Applied Systems Analysis, W. Häfele, Program Leader (1981); this reference is abbreviated as Häfele (1981) also in the following.

In this section, a view of the future is examined, which uses these macrosystem characteristics as a guide. The heroic transitions are mathematically modeled in Marchetti and Nakicenovic (1979). Briefly, the competing technologies are ordered chronologically, i.e., in the sequence they appeared on the market. The market share F is described by the logistic function $1/(1+e^{-\alpha t-\beta})$ where the coefficients α and β are determined from historical data. This produces a straight line on a semi-log graph with some energy sources ascending while others are descending. The trick is how the saturating technology is treated. On a global basis the oldest currently ascending technology is oil. Its share is simply one minus the sum of the shares of all the other energy sources. A criterion is established (Marchetti et al., 1978) to set the end of this bending-over transition, and the resumption of a logistic relationship (now downward). The model, of course, does not predict when a new energy source will enter the mix, nor at what rate it will ascend. However, this approach lends itself to easy speculation of energy futures and provides a simple tool that has a vast amount of historic system behavior built into it.

We start with the observation that, just as coal replaced wood and oil relaced coal, natural gas is likely to replace oil (first in/first out). This possibility would have to be based on gas being more than a byproduct of oil fields, and the gas industry being institutionally different than the oil industry. Although these are not commonly held views, they are reasonable possibilitites (Gold and Soter, 1980).

This observation is reinforced by the macro-system characteristics of gas. Specifically, possible improvements of natural gas over oil in transport, storage and certainly in end-use convenience are now driving it to replace oil today on a global scale, especially for stationary uses and uses that involve only continental transport. For intercontinental transport of gas, LNG (liquified natural gas) is required, and this introduces an extra step in the process. However, this extra step is not unlike an extra step in the oil system, namely refining.

For the ground transportation sector, the end-use handling of oil is fairly well matched to the truck, bus or auto end-user, and natural gas seems to have no particular advantage in the current apparoach to ground transport. In fact, gas would probably be transformed into methanol for use in ground transport. Thus, in the use of liquids for transportation, one of the four major end-use categories estimated to consume about one-quarter of the energy used globally in 2030, there is no obvious advantage for gas over oil. Therefore, as gas replaces oil in the other major use categories, there may be a residual use for oil in transportation based on these macro-system streamlining considerations.

However, even this residual use of oil for transportation may be smaller than what would normally be expected. Just as cars replaced trains in 1930 as the dominant intercity people mover in the US, the use of cars peaked in 1960 and is being overtaken by air transport as the primary method of moving people between cities. Thus by 2020 the dominant uses of energy in intercity transportation in the US probably will be in air transport (Marchetti, 1980); and global trends usually follow the US by 15-30 years. This combination of a decreasing role for oil and increasing role for gas, along with air transport likely to dominate intercity transport, sets the stage for an interesting situation. Some suggest that for a combination of reasons the use of liquid hydrogen (LH_2) promises to replace kerosene as the air transportation fuel of the future (Brewer, 1975). Some of these reasons are the favorable energy-to-weight ratio (if not volume), low emissions and primarily the increased substitution of natural gas for oil. As airports become fewer in number, with enormously greater concentrations of energy throughput, this means gas pipeline delivery is more convenient (more streamlined system) than oil trucks. LH_2 would be generated at the airports directly from natural gas.

The use of natural gas directly in ground transportation most probably will take the form of compressed gas bottles (CNG), used today for 300,000 cars in Italy alone. The pipeline gas at about 100 atm would be further compressed by a factor of 2 for use in steel bottles at "gas stations" located near the transmission pipeline. Even low pressure distribution system gas can be compressed to 200 atm at greater than 90% efficiency considering the efficiency of the source of mechanical energy. These vehicles would have a more restricted range ($\simeq$200 km) and would be suitable for in-town travel. Thus, even if hydrogen from natural gas did not see much use in transport beyond aircraft, natural gas could be used directly for intracity ground transport as CNG. "Gas stations" would for the first time be aptly named.

Thus the substitution of oil by gas will probably be on a larger scale than one would normally think. It could include most of the transportation sector and set the stage for the extensive movement of cryogenic liquids in ocean tankers and the first major use of hydrogen in a stand-alone fuel use (aircraft). (The current and substantial use of hydrogen, which is 5% of global energy based on heat content, is entirely for chemical feedstocks.)

With these possibilities in mind, and remembering the trends suggested by Figure 1, let us extrapolate past trends qualitatively to the following plausible energy future as shown in Figure 2 (Marchetti and Nakicenovic, 1979). These future projections feature a range of nuclear introduction from 1% to 4% market share by 2000. In complementary application, each of these choices has efficiencies from 50% more to 3 times greater than current use of gasoline in conventional engines.

Gas may replace oil with peak penetration around 2040 as discussed previously, and nuclear (burner-breeder) may overtake the gas market share essentially by 2060 and peak by 2100.

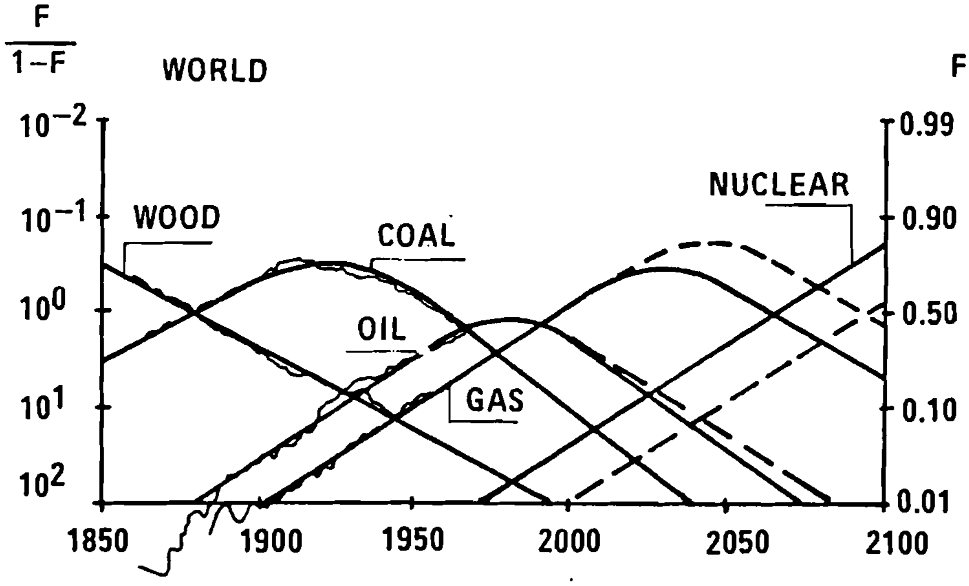

Figure 2. Business-as-usual projection of world primary energy mix. The dotted line is delayed introduction of nuclear (burner-breeder), or possibly solar energy (Marchetti, 1977).

Nuclear may replace gas as a convenient site can be chosen rather than having to rely on the geological accidents that determine gas field sites; there are also advantages in transmission, storage and end-use.

By nuclear we mean here not only nuclear electricity but also nuclear hydrogen, in gas and liquid forms, nuclear hydrogen/ methanol with a coal, biomass or limestone carbon source, and finally nuclear heat directly to users. This use of nuclear energy is based on a widespread social acceptance that it is desirable, and the ending of the current widely based societal resistance to its further development. Thus the extensive use of natural gas might pave the way for a nuclear hydrogen and nuclear electric successor. Also shown (dotted line in Figure 2) is a later introduction of nuclear. This would hardly affect oil usage according to this model of energy substitution dynamics, but it would extend the use of gas. This would raise some real questions about actual gas depletion based on estimates of the ultimate gas reserves from biological sources.

Note that in imagining such a progression no allowance has been made for "new coal", reborn again and used in the form of synthetic liquids and gases. This is certaintly possible and is actively being pursued by several countries, and would certainly be useful in extending the fossil era. This would avoid the possibility of biological natural gas becoming depleted if the follow-on energy source to gas is delayed. However, non-biological gas sources may be very significant (Gold and Soter, 1980), and easily sustain this use of gas.

The future that we have just sketched out suggests that solar penetration will be limited to, first, some use of biomass as a carbon source if methanol is used for some of the transportation or remote site fuel needs, and second, a host of small uses of solar energy where it is marginally economic. Certainly, solar does not appear to be able to contribute much of an improvement along the lines of greater macro-system "convenience" over this nuclear energy future; if anything, solar seems to have greater difficulty being integrated in energy systems, owing to its intermittent nature. This is especially true when one looks at solar energy by viewing each specific solar application individually and then thinking of "solar" as just the sum of separate applications. A second apparent disadvantage of solar is that it counters the historic trend toward increased energy density in energy supply as well as in energy use. Solar is a diffuse energy source at a peak direct terrestrial insolation of about 1000 W/m^2, which is about 300 W/m^2 on a continuous bases--this is far less dense than coal, gas or nuclear resources at the mine or well.

Thus system "convenience" and incrasing energy density do not seem to be solar's strong points. According to the above line of reasoning, then, one would expect nuclear to play the next major role and begin to dominate gas about 2060, with some, but small, inroads from solar where it is marginally economic.

These trends in macro-system behavior indicate that, if solar systems become a global energy option, they will inherit a world dominated by one of two significant possibilities. The first is one filled by natural gas distributed globally by LNG tankers and continentally via pipeline directly to end users. The second is one where nuclear power has taken over from gas and produces electricity distributed via the electrical transmission and distribution system, but more importantly by generating hydrogen distributed globally via LH_2 in tankers and continentally via pipelines directly to end users. Even if coal is reborn again as synthetic fuel, it would also see significant use as synthetic gas or liquid, not as a solid. In all cases, a residual use for liquid for some transportation and remote sites could be met initially from oil and eventually from methanol made from natural gas, or nuclear hydrogen and natural gas carbon or coal carbon. This sets the stage for considering a global solar possibility.

SOCIAL PREFERENCES

In both the substituion of oil for coal and the possible substitution of gas for oil, the replacement fuel has the characteristic of being more environmentally attractive than the fuel it replaces. However, this may be only an unintended but beneficial side effect resulting from the drive to smoother and more convenient system operation. Still it is a curious harbinger of a social phenomenon that has been occurring over the last decade and appears to be strongly influencing the sorts of social preferences, or definitions of convenience, that might emerge in the future.

One symbol for this new dimension of social importance is the view of the earth from the Apollo spacecraft as it approached the moon in 1969. The earth looked beautiful, but very small and delicate with only a very thin blue rim and clouds to indicate that a life support system was operative. This event, in a very dramatic way, gave expression to the developing awareness of earth's limited nature and environmental fragility. So although the past can be seen to have been driven by system streamlining on a macro level without regard to much else, but apparently within reasonable bounds of economics and resource limits, the future may have to accommodate additional factors touching more directly on psychological limits and social needs other than energy per capita. The very same technical industrialization factors that have given rise to increased urbanization, with an associated increase in the size of organizations, have resulted in human depersonalization and an increased sensitivity to crowding and environmental degradation. The use of marginal economic efficiency as the prime criterion for decision making at individual and corporate levels has also stripped the human environment of much of what is human. Consumerism as the primary motivating force in some developed countries may be grossly deficient as a basis for human fulfillment and happiness. These excesses, which seem destined to continue in an endless fashion, seem to be producing a climate for evaluating the current social/economic basis of market as well as planned economies.

Thus, future energy transitions may have additional driving forces in addition to those of the past. These driving forces may require a minimum level of environmental acceptability, a minimum level of individual human controlability, or a minimum level of human understandability in terms of either system or technical complexity. There may also be an upper limit to the allowable potential damage that can be associated with an energy system regardless of the calculated probability of the damage occurring. The existence of these new forces can be clearly seen by observing the events surrounding any large energy project. As a society our understanding of these new forces is still weak, and confusion during this transitional period runs rampant.

Attempting to project the future is under the best of circumstances a risky business but predictions during this profound period of social transition are especially risky. One's view of the likely possibilities of the future depends to a great extent on the perceived reality of these social forces. See Reuyl et al. (1977) for insights into how perceptions of reality can affect judgments in energy matters.

Still a significant if poorly understood transition is occurring that threatens to upset the neat and tidy view of the future suggested in the oil through natural gas to nuclear energy trajectory just described. Additional social factors may become fully integrated into the future definition of "societal convenience and preferences stimulated by technology within a macrosystem context". If this is so, it may tend to limit or possibly exclude certain future energy systems, thus providing the basis for a greater if not dominant role for solar energy.

Given such a possibility, it is worth our while to ask if solar has the potential to take over so great a long-term role, or is it in some sense inherently limited. Put another way, the question is whether there exists any "factual basis" for summarily dismissing solar as a possible mainstay of a future energy system. In the next section we examine each of the potential weaknesses that might compromise an energy system depending substantially on solar.

The areas that are inspected briefly to obtain a sense of this overall question are: the magnitude of the solar resource, the ability of the solar system to be smooth and stable, the relative economics compared with more conventional systems, the efficiency in the use of resources and material, environmental impacts, sociocultural suitability and some political considerations.

POTENTIAL LIMITATIONS TO SOLAR ENERGY

Possible Fuel (Insolation) Constraints

How much solar energy is possible, of what kinds and in what system arrangements?

Solar energy can be divided into three arbitrary categories: dispersed direct, indirect, and central direct. In addition, these technology categories can be arranged at five system levels: on-site, neighborhood or village, national, continental and global.

Dispersed direct solar has systems at the on-site as well as neighborhood or village level, using direct solar equipment for heating, cooling and electricity in active and passive systems. These are shown primarily in Figure 3.

Indirect includes wind, ocean thermal energy conversion (OTEC), all manner of biomass including wastes from current activities as well as planned production. These solar systems are shown primarily in Figures 3 and 4, and can be arranged from the on-site to global system level. Hydroelectric, both large and small, are also included.

The central direct solar systems use large solar thermal and photovoltaic plants and can be used at the national level as shown in Figure 4, or at the continental and global levels as shown in Figure 5.

Central Solar Resource

Each of us is aware that the sun daily sends enormous amounts of energy to the earth. The average power input from the sun is some 178,000 TW(th). The world currently uses energy at the rate of 8 TWyr/yr. A straightforward calculation can show the resource potential of large-central solar energy.

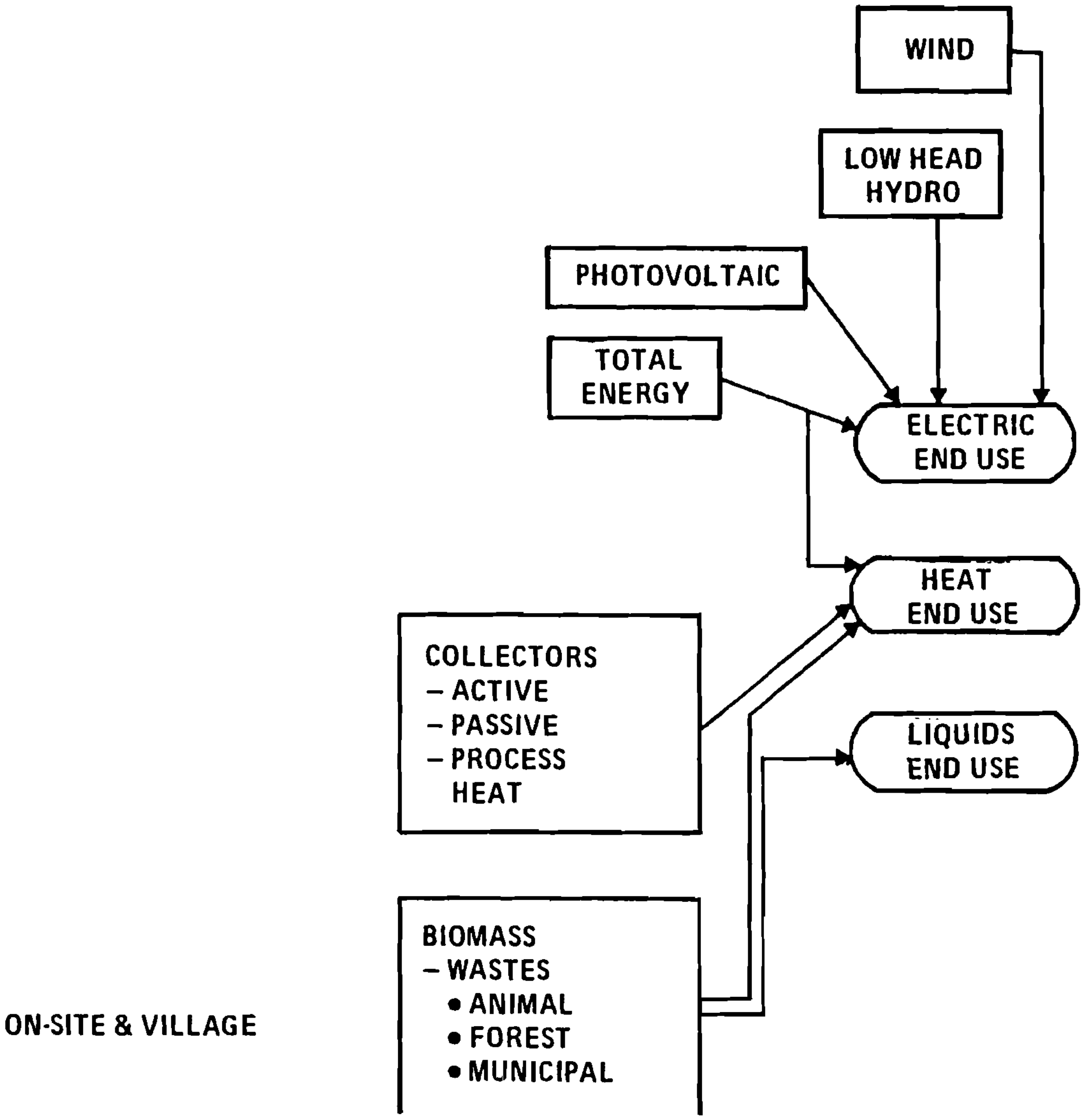

Figure 3. On-site and neighborhood (village) level solar systems.

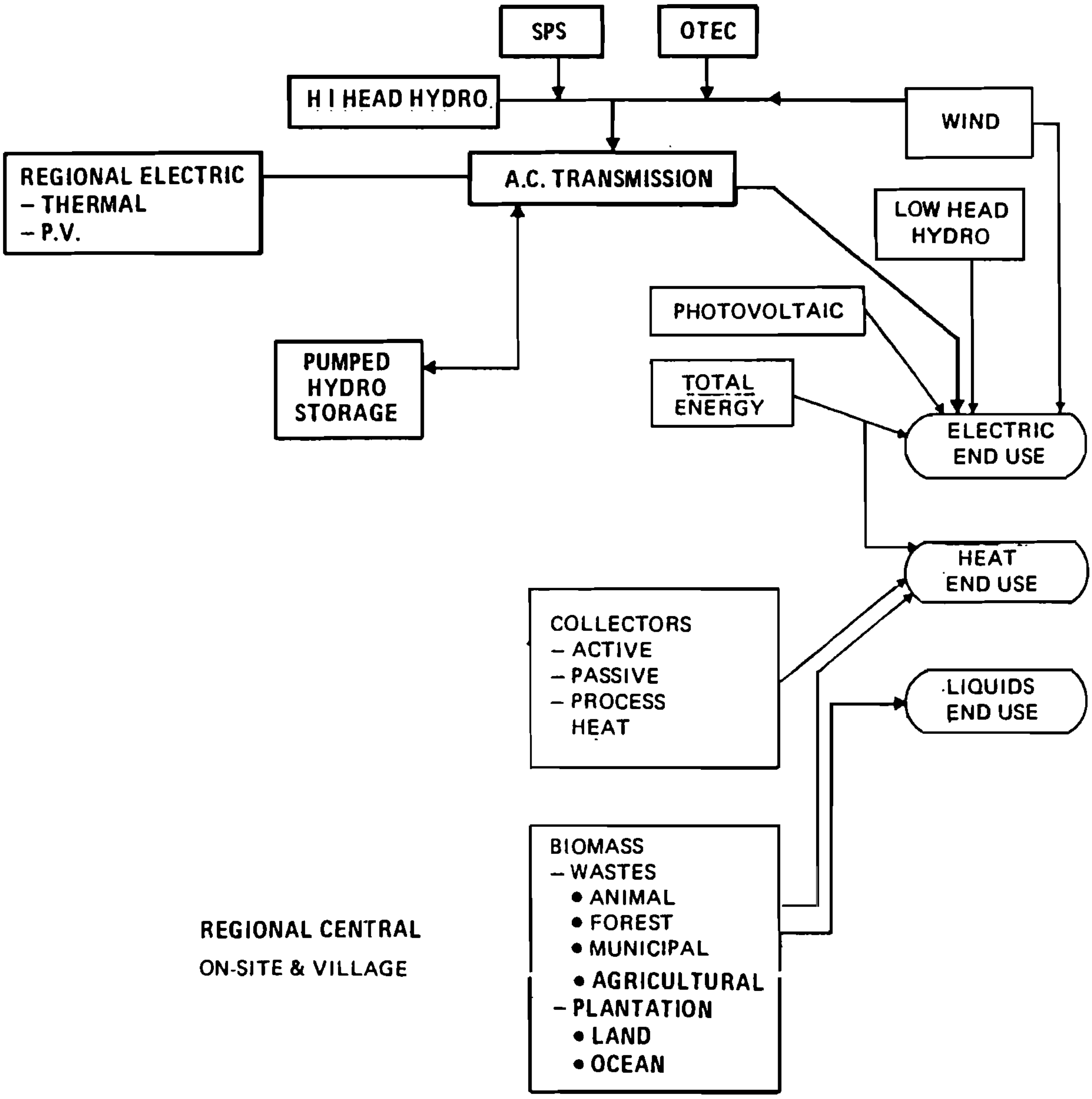

Figure 4. National level central solar systems.

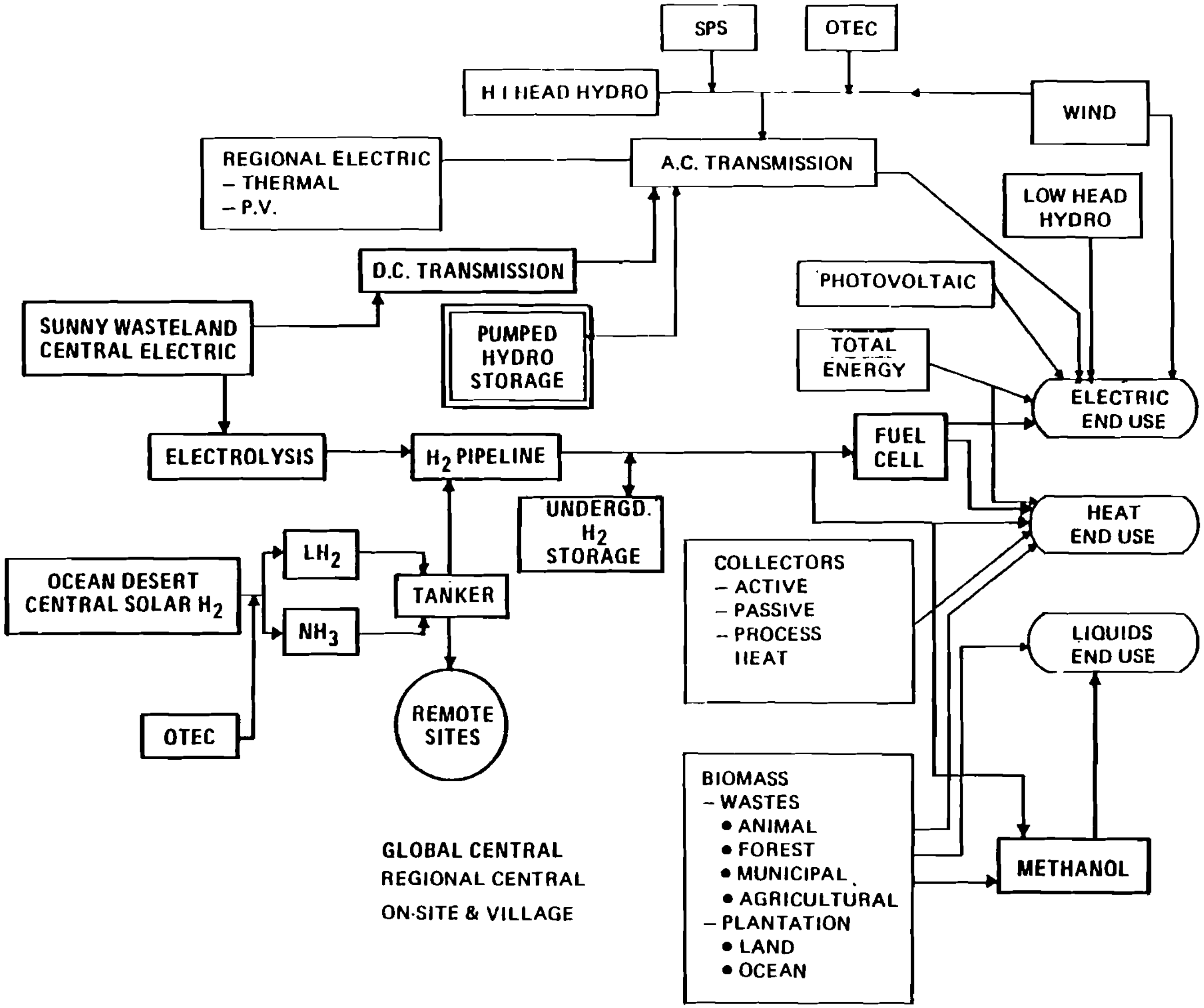

Figure 5. Global central solar.

Terrestrial central solar systems

A typical central solar system would eventually (>2030) be based on hydrogen. It would be used as we imagined natural gas being used when it played the dominant role in the global energy mix. That is, pipeline hydrogen would probably be used in the existing gas pipeline grid for transmission and final distribution to the load center as shown in Figure 5. It would be used for heating, electrical, chemical and transportation end uses. Electricity via fuel cells would be used on both the on-site level and the district level (neighborhoods), the two being connected via the electric grid. In both cases waste heat would also be utilized. Internal combustion Stirling engines might be used instead of fuel cells. Lighting could be done directly with hydrogen, via chemofluorescent phosphors or with electricity. As discussed previously, the transportation sector would employ LH_2 for aircraft as well as some ground transport, and electricity would also be used for ground transport. Methanol from hydrogen and a biomass carbon source would have a limited role in ground transport and as a remote site energy source (not connected to the pipleine grid), or as a back-up system. Moreover, if the central solar systems use electricity as in Figure 5, and are within reasonable high voltage DC transmission distance (1800 to 3600 km), then this electricity would be directly transmitted to load centers and distributed via existing distribution systems. It would be backed up by pipeline H_2 stored underground and used via fuel cells. If thermo-chemical hydrogen production is used then long distance electric transport is unlikely, since hydrogen pipelines would be used.

Based on good desert locations, the direct, normal radiation is about 2750 $kWh/m^2/yr$, which is equivalent to 314 W/m^2 continuously. To meet a 10 TWyr/yr primary energy demand assumed to be made up of 25% electricity, 25% transportation liquids and 50% heat, only 0.16 to 0.43 $\times 10^6$ km^2 of remote land would be required. This amount of land is similar to that used for human settlements (0.4×10^6 km^2), and is only a small fraction (1% to 2%) of the arid sunny land, which is approximately 20×10^6 km^2 or 15% of global land.

The range of land requirements depends on the solar system efficiency in utilizing the solar resource. Nominal values are chosen for each stage of the two suggested systems shown in Figure 5. The principal links are the solar to electric (considered to be 20% efficient), solar to high temperature heat (taken as 70%), heat to hydrogen (at 60%), electricity to hydrogen (90%), electric transmission (90%), and hydrogen to electricity (70%). The result of these assumptions along with 2750 $kWh/m^2/yr$ of direct beam desert insolation and a ground cover ratio of 0.3, are that a solar system performance of 23 TWyr/yr per 10^6 km^2 to 62 TWyr/yr per 10^6 km^2 is achieved based on land area. The energy is the primary equivalent, meeting a combination of end uses.

Even the 2030 prediction of 35 TWyr/yr used in the global high scenario (Häfele, 1981) can be met entirely from central solar systems using 0.6 to 1.5 $\times 10^6$ km^2 of remote sunny waste land. This represents about 3 - 7.5% of this arid land resource. But how much land can reasonably be used?

As a frame of reference, a study of remote solar plant siting done for the southwest US (Aerospace Corporation, 1974) indicating that 2 - 16% of the total land in an erea comprising eight states was potentially available. These states (California, New Mexico, Arizona, western Texas, Nevada, Utah, Colorado and Oklahoma) represent one-third of the total continental US land area, and the range 2 - 16% represents 0.05 to 0.40 × 10^6 km^2. The approach taken is to list reasonable exclusion criteria: land on a slope greater than 20^0, land covered by sand, land with any reasonable crop or grazing potential, any land with forests, land owned by Indian tribes or used as a local, state or Federal park, etc. Some more stringent criteria were also introduced, which, for example, excluded all Federal lands (which in one of these states amounted to half the land area). A second study of seven countries of Southern Europe shows that a range of 0.9% to 5.5% of the *total* land area could be potentially made available for solar energy use after applying all the relevant constraints (Doblin, 1981). This is substantially in agreement with the 2 - 16% range when differences in land-use characteristics are considered.

The waste, desert and mountainous regions of the world, exclusive of uninhabited islands and polar areas, cover 62 × 10^6 km^2. It is rather arbitrarily assumed that 20 × 10^6 km^2 of this land (15% of global land) is even worth considering for central solar systems as arid sunny wastelands. It is interesting to note that about 4% of the southwest US land is considered sunny wasteland and this was in the lower end of the range of the 2 - 16% range of availability mentioned above. The balance of the area available for solar in the southwest US comes from suitable low-use grazing land. Even if one conservatively applied the range of 2 - 16%, not to the total land area but only to this estimate of arid sunny wastelands of the globe, the available land area would be 0.4 × 10^6 km^2 (0.3 - 2.4% of total global land).

A completely independent estimate (based on the World Atlas of Agriculture, 1961) of potential sunny wasteland excluding sandy regions and lower-use grazing land, gives a land area of 4.3 × 10^6 km^2. This agrees well with the 0.4 × 10^6 km^2 to 3.2 × 10^6 km^2 estimate and substantiates its conservatism.

Making simple assumptions that the range of land availability is about a one sigma variation (67% chance of available land being in this range), and that the solar system efficiency range is also about a one sigma variation (67% chance of system performing in this range of 23.3 - 61.7 TWyr/yr per 10^6 km^2 of primary energy equivalent), then the expected range of resulting central solar energy delivered is 14 - 130 TWyr/yr with 67% confidence as shown in Figure 6. This is quite interesting when compared with the range of energy use in 2030 as calculated in Häfele (1981), i.e., 16 - 35 TWyr/yr.

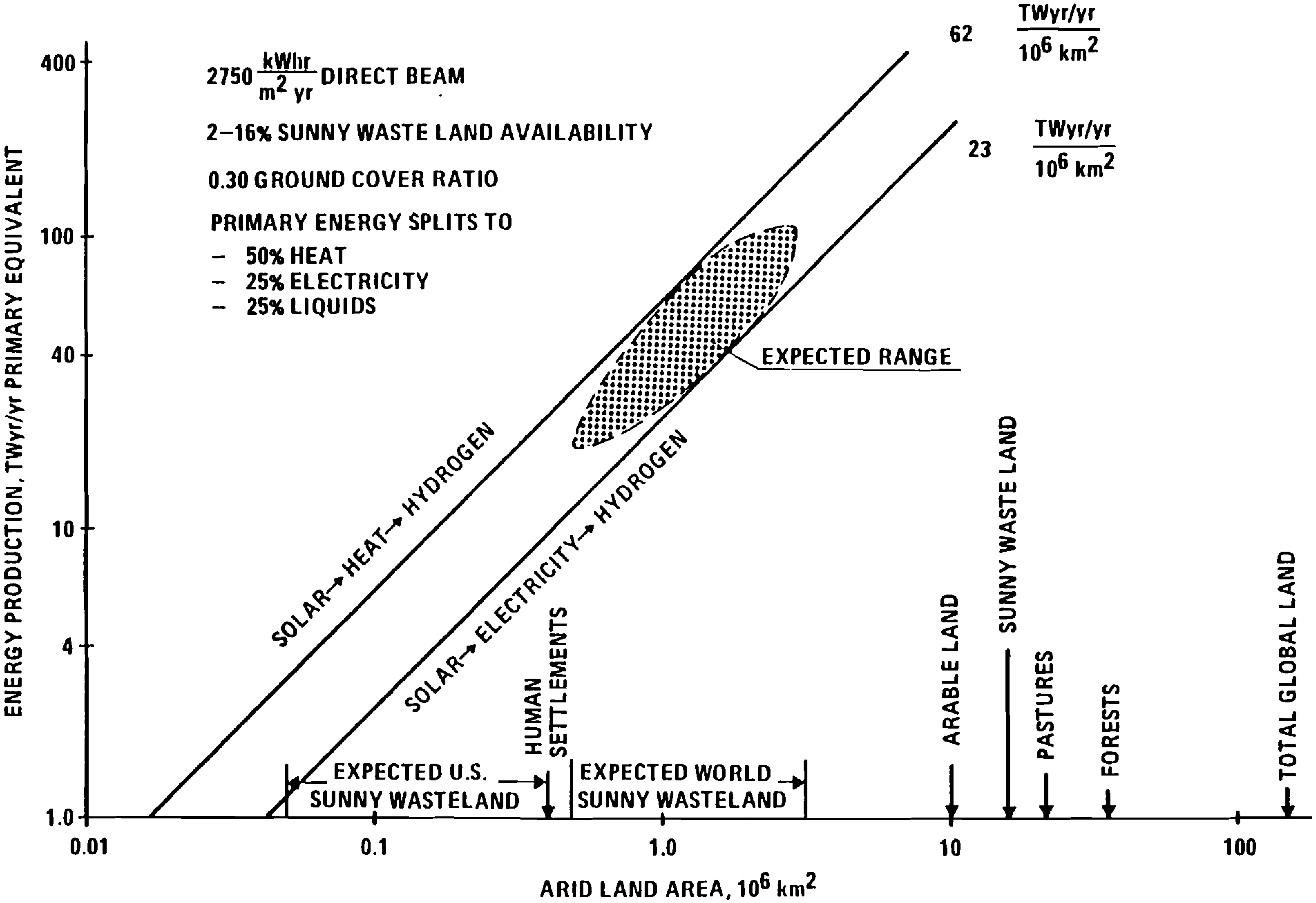

Figure 6. Global desert - central solar energy production.

There are a number of land areas globally that have the combination of good sunlight and low current usage (Figure 7) (Oliver, 1979), such as southwestern US, northern Mexico, and northern Australia, south central South America, the Caribbean area, and most of north central Africa, some of south central Africa, the mid-East and southwest Asia. Thus, eight distinct significant global regions have a large central solar resource with at least one area on each continent excluding Antarctica. The only other areas relatively deficient in good direct beam solar energy are northern North America, northern and eastern Eurasia, and tropical areas. Ironically enough, the large central solar resources exist near large natural gas fields. As these gas resources are developed with the investment in pipeline infrastrucure to nearest large load centers, these equipments and right-of-ways could be eventually used by solar generated hydrogen as part of the mix of solar-derived energy.

Ocean central solar systems

In addition to the areas just mentioned, there are large desert areas on the oceans, which avoid the land-use question entirely and allow designs that take advantage of the ocean environment (Escher et al., 1977). These ocean designs may exploit characteristics of the ocean such as a low-friction bearing surface, which permits easy rotation of the platform, thus eliminating one axis of rotation in the solar collectors. The platform will probably be supported by a flotation system, which uses a cluster of upright capped cylinders that are ballasted and thus act as columns passing through the air/water interface to the platform. A cable suspension system could be used to support the platform from a central vertical column.

Advantages of such a system would be: the avoidance of conflicts with competing land uses; access to low temperature water for cooling, and water as a feedstock for hydrogen generation; ease of logistics for global distribution; and a standardized ocean environment that avoids the higher costs associated with site-specific design. Potential problems are: the ocean is a dynamic interface with currents and winds offering disturbances that must be successfully desinged for a long-life system; salt water corrosion; marine fouling; legal uncertainties about ocean rights; and whether a low cost commercial design can be assumed.

The ocean areas should substantially increase the potential of this central solar approach to global energy. Suitable ocean areas seem to exist: in the mid-Pacific approximately between latitude 0° and 20° south and lontitude 120° and 130° west; and in the mid-Atlantic between latitude 0° to 10° south and longitude 10° to 30° west, and possibly in the Indian ocean as shown in Figure 7 (Hastenrath and Lamb, 1977; and Atlas of Thermal Balance of the Globe, 1973). Considering the first two of these

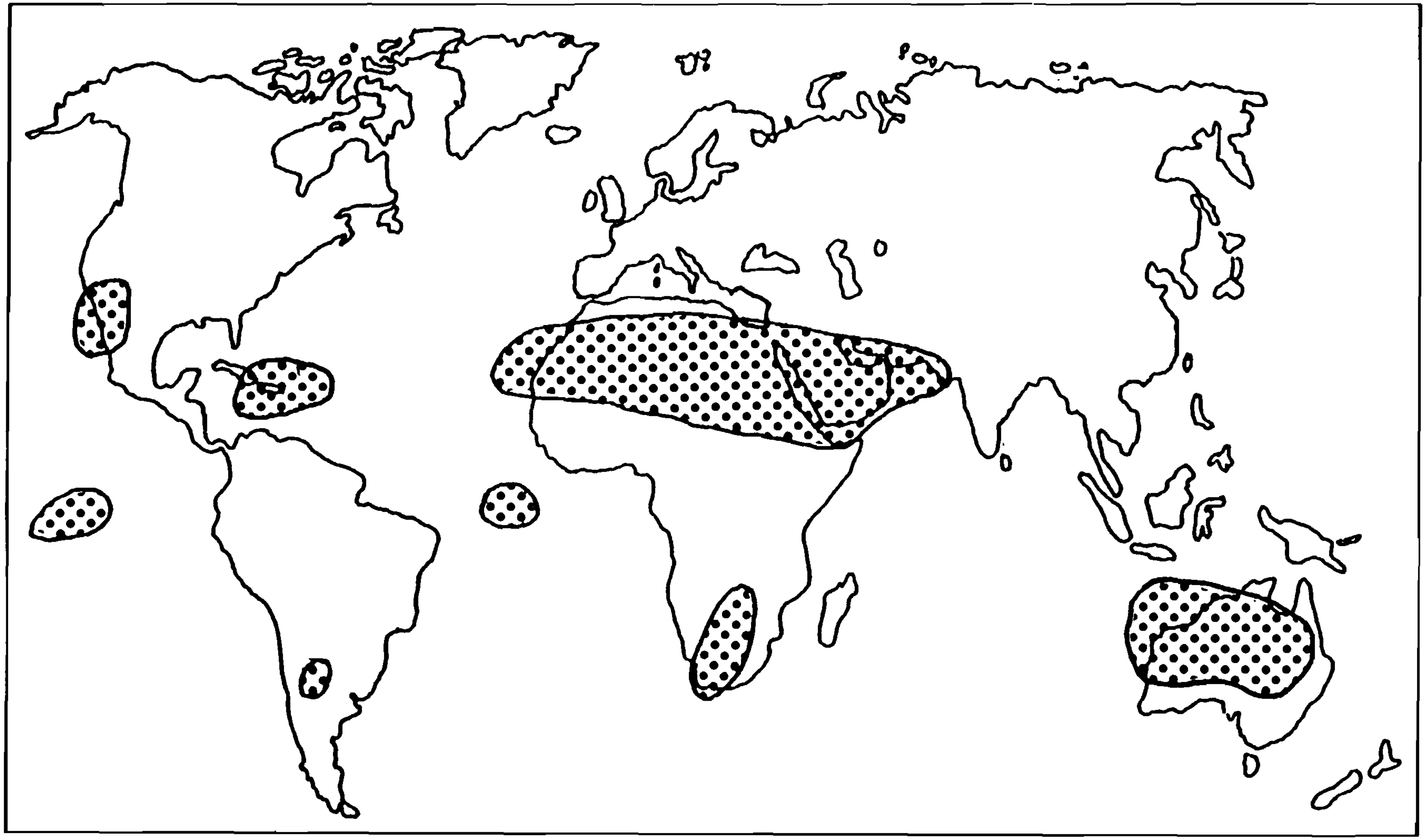

Figure 7. Good global solar areas.

three ocean areas, this represents roughly an ocean area of 5.3×10^6 km^2 and would generate 43 - 114 TWyr/yr of LH_2 even if only half of this area was used.

The only significant difference relative to land systems would be the use of cryohydrogen and possibly ammonia as the energy carrier for all the energy. In Figure 8 this ocean transport path is shown as parallel to pipeline hydrogen, and applies to both ocean systems and transmission via tanker to isolated load centers such as Japan.

Solar power satellites

In addition to sunny wasteland and desert ocean areas, the third major central solar possibility is orbital solar power satellites (SPS). The SPS most probably would use photovoltaics and the electricity produced would be converted into microwave energy and beamed to the earth where it would be reconverted to electricity before transmission to the load center.

Although these solar plants are in synchronous orbit located 36,000 km from the earth's surface, they do require energy receivers (rectenna) on the earth's surface, which take about as much area per unit energy as a central solar electric plant would require if the USSR microwave standard is used to define the boundary of the facility. However, these SPS ground facilities do not depend on *sunny* waste regions, but only on low use or waste lands up to about 50^0 latitude (mid-Europe). This characteristic will be especially beneficial for those regions not located convenient to the eight sunny waste regions identified earlier.

The resource potential of SPS solar plants is large and may exceed 6 TWyr/yr of primary equivalent energy before serious questions are raised about starting to saturate the parking spaces available at geosynchronous orbit. (4.5 TWyr/yr electric is produced by about 1000 five GW(e) stations.)

Indirect Solar Energy

No attempt is made here to do an indpendent estimate of the indirect solar resource, which would include wind, hydro, OTEC and biomass. Based on Häfele (1981), the technical potential of indirect solar sources is estimated to be about 13 TWyr/yr. This is reduced to 9 TWyr/yr through various judgmental limitations with a primary equivalent of 13 TWyr/yr. The basic components of these solar systems can be found in Figures 3, 4, and 5.

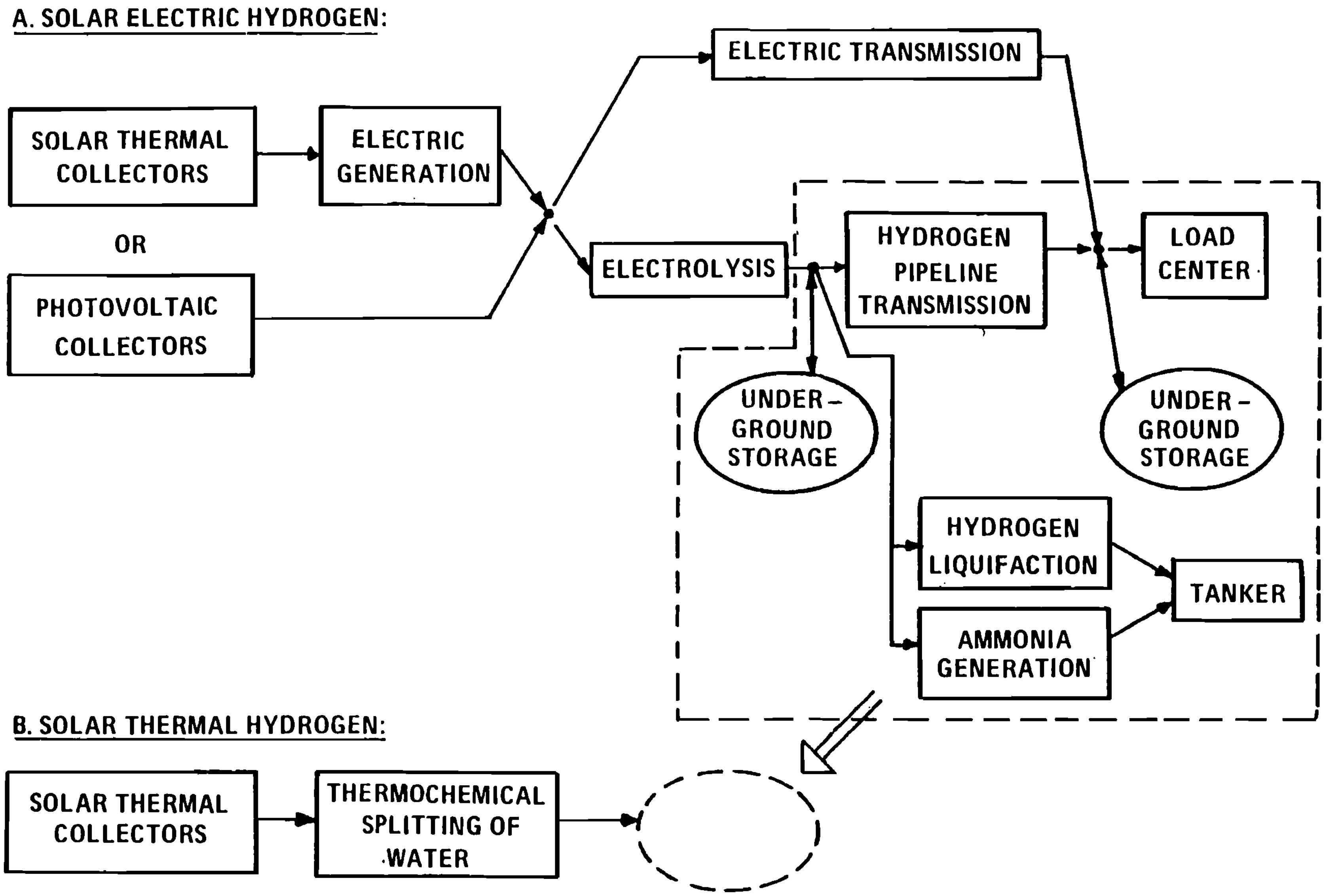

Figure 8. Two simplified central solar systems.

Dispersed Direct Solar Resource

Nestled between indirect and central solar are on-site and neighborhood (village) direct solar systems, as shown most clearly in Figure 3. To estimate the eventual (>2030) potential, the following assumptions are made, using where possible the guidelines used in Häfele (1981). The estimates of direct, local solar, utilization are based on the California study (Craig and Cristensen, 1978) adjusted for developed, temporate regions, and are as follows (excluding photovoltaics).

For developing regions:

- Buildings
  - 70% of hot water
  - 25% of electricity and 10% of this is available as waste heat for space heating
  - 14% of space heating from roof collectors and passive heating
  - this averages 25% of this end use sector (0.36 TWyr/yr)
- Industry
  - 70% low temperature heat
  - 58% high temperature heat
  - 60% electricity
  - this averages 40% of the end use sector (3.38 TWyr/yr)

For developed regions:

- Buildings
  - 44% of space and water heating
  - 8% of electricity and 20% of this available as waste heat for space heating
  - this averages 37% of this end use sector (1.63 TW)
- Industry
  - 47% of total (5.4 TW)

The total of all uses of direct solar for on-site or neighborhood energy systems is 10.8 TWyr/yr as the eventual potential as part of a 35 TWyr/yr global demand. This is greater than the 2.28 TWyr/yr estimated in Häfele (1981) due to differences in the time frame (2030 versus "eventually"), and in the consideration of economic acceptability.

On-site photovoltaic should also be considered. If commercially available on a large-scale basis, it could be used on roof tops and south facing walls without land-use or transmission-line impacts. Roof area is estimated to be 0.11×10^6 km^2 globally (UN, 1976; Austrian Stats., 1975). Using photovoltaic on 1/3 of this would amount to 0.04×10^6 km^2 of roof area in the load center available for electricity generation. Based on the total insolation being 1400 kWh/m^{2}yr (1/2 the desert amount) and on a fixed tilted surface in an average and more temperate location, the primary equivalent energy represented by this roof area is 1.9 TWyr/yr at a 10% system efficiency.

Using half the available amount of waste heat increases this by 2.9 TWyr/yr to a total of 4.8 TWyr/yr.

Thus the potential direct solar contribution would increase from 2.28 in Häfele (1981) to 16.8 TWyr/yr when we include roof top photovoltaic, on-site and neighborhood direct total energy systems, and direct heating use in the developing world. These indirect uses of solar energy could constitute a global energy source. Their significance depends on the total amount of energy one assumes will be used in the future, the judgmental values one applies to limit solar, and whether these divergent sources called renewable energy can be conveniently arrayed into a global system. This last question will be discussed more fully later in this chapter in the section on system streamlining.

Considering this source along with central solar or sunny wasteland, ocean and orbital plants, raises the potential solar contribution to a range of about 80 to 280 TWyr/yr as shown in Table 1. This is about 1/1000 of the 178,000 TWyr/yr of solar energy that strikes the earth.

Showing that 80 - 280 TWyr/yr of solar energy could be used globally should not be interpreted as a recommendation that this much energy should be used, or a prediction that this will occur. It simply is a resource limit check to see if the magnitude of the global resource is a limiting factor in consideration of its use. It is sufficient.

Before moving on to potential difficulties in steamlining a solar system, a final observation is in order. Several

Table 1. Potential solar[1] contribution, TWyr/yr

Indirect solar (wind, biomass, hydro, ocean thermal, etc.)	$\simeq$ 13
Direct solar	
Dispersed	
- solar thermal	3-16.8
- photovoltaic	1-4.8
Central solar	
- desert	14-130
- ocean	43-114
- orbital	5-10
Total	79-283

[1] This considers all renewable sources with solar energy as the origin, both direct and indirect, and including biomass up to 10 years old. Geothermal energy is not considered.

studies on the national level have considered the ability of a family of solar options to provide the entire national variety of end-use needs (Johansson and Steen, 1978; Le Groupe de Bellevue, 1973; Krause et al., 1980; Oliver, 1979). Even for a country like Sweden, which is located at high latitude, it is possible to use solar energy for 100% of its energy needs when there is a combination of biomass, wind, active collectors with seasonal heat storage, and photovoltaics. This in some national, as well as global situations, solar is not resource constrained.

System Streamlining Characteristics

The use of the concept of system streamlining as a major driving force in the evolution of energy systems seems to be very useful. As presented in the introduction, the observation that solar is "awkward" in this important characteristic owing to its intermittent nature and its apparently severe storage requirements deserves some examination. We start with two examples of how the awkwardness of solar shows up in calculations.

First, many observers have focused on each solar system as a separate and isolated unit. Based on this perspective, economic studies confirm that for typical housing and for technologies such as active or passive solar, building heating should be sized to contribute 40% to 80% of annual demand at the optimum design point (i.e., one to four days of storage). Based on such design goals the cost of 100% solar at each site turns out to be prohibitive.

A second example has to do with the contribution solar can make towards meeting winter heating demand. In the more temperate regions (i.e., central and northern Europe) the winter heating demand in these regions occurs when the solar input is very poor based on global insolation on a horizontal surface. Choosing Munich, FRG, in central Europe, for example, the ratio of monthly average global insolation from summer to winter is quoted (T. Ward, personal communication, 1980) at six to one. However, basing the calculation on horizontal radiation exaggerates the variation since active collectors are usually tilted toward the equator. For winter heat collection the collectors are usually set at the latitude angle plus 10° to 15°. For *annual* maximum collection, as in the case of hot water heating, collector tilting at the latitude angle is usual. These typical design practices moderate the seasonal imbalances significantly. For example, when placed at the winter heating tilt angle, the summer to winter insolation ratio is moderated to 3 to 1 at Salzburg, and 37% more insolation is intercepted during the five month heating season than would be the case given horizontal orientation. However, to properly evaluate the potential of solar it is important to step back from individual sites and specific systems and to consider the overall system.

The overall and "eventual" solar system would be made up of the full family of solar systems such as

- On-site
  - Active Collectors
    - Building heating and cooling
    - Hot water
    - Industrial process heat
    - Agricultural process heat
  - Passive Heating and Cooling
  - Electric
    - Thermal
    - Wind
    - Photovoltaic

- Neighborhood (village) systems
  - Total energy (co-generation with thermal or photovoltaic)
  - Electric
  - Thermal
  - Wind
  - Photovoltaic
  - Small hydroelectric
  - Heating

- Biomass

- Wastes - Plantation	to gas to liquid to solids	on-site, village or central

- Central electric
  - Wind
  - Hydroelectric
  - Biomass
  - Photovoltaic
  - Solar thermal
  - OTEC
  - SPS

- Central hydrogen
  - Solar thermal chemical hydrogen
  - Central electric hydrogen

Simplified system arrangements are shown in Figure 3 for on-site and village level systems, Figure 4 for national level central systems, and Figure 5 for global level central hydrogen systems.

The solar system described in Figures 3, 4, and 5 can be considered to come into existence in four stages. This "eventual" solar system can be considered to be stage 4 in a hierarchy of transitional solar systems. One of the most important aspects of these stages is how the back-up or storage function is provided. Figure 9 shows a representation of these dynamics. In stage 1, the system back-up or storage is provided by fossil fuels. Biomass, pumped hydro and controlled release of hydro as well as seasonal heat storage are introduced to take over some of this role from fossil fuels. Eventually in stage 4, continental and global central solar hydrogen is added to these to

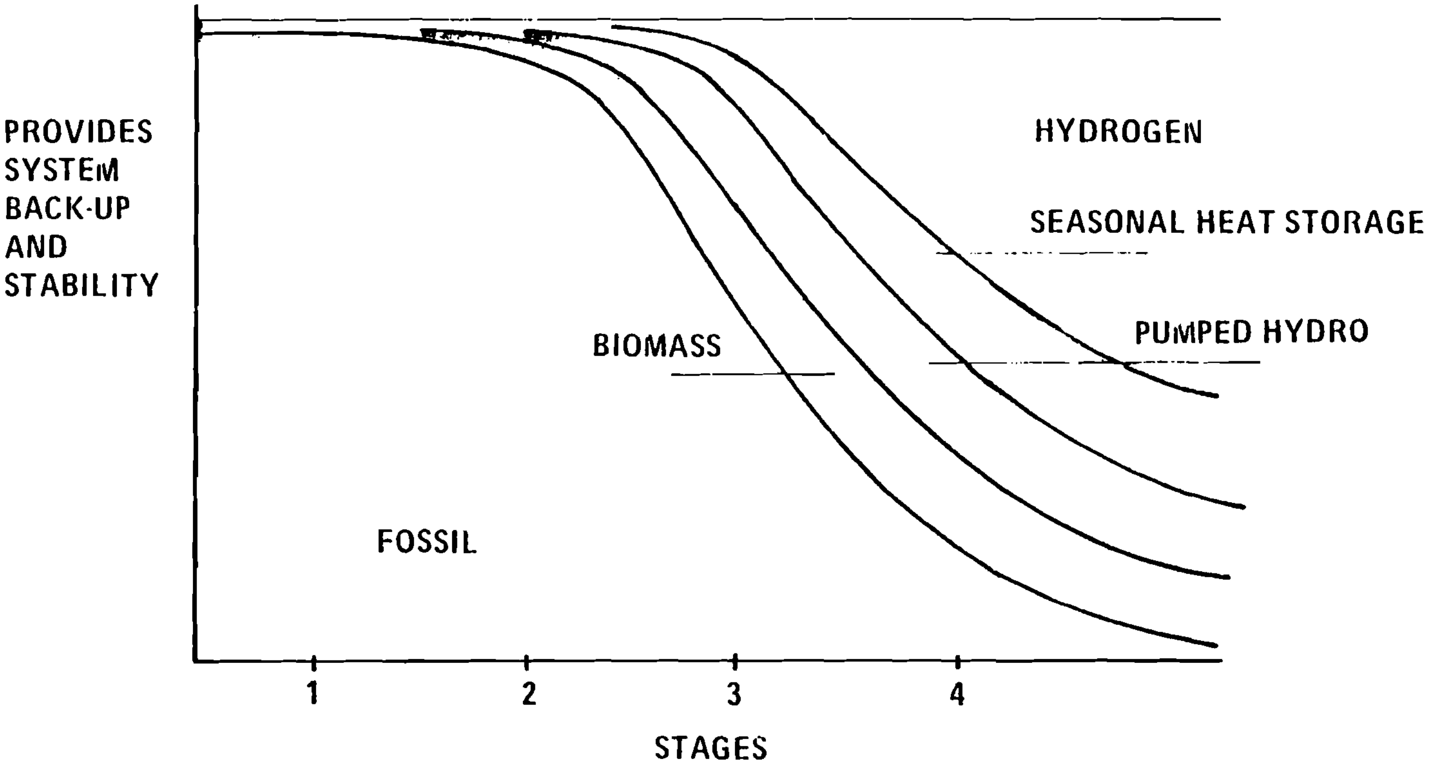

Figure 9. Source of system back-up or storage.

replace fossil fuels as the source of system back-up. The magnitude of each contribution and the exact phasing of this transition is not developed in this paper. To illustrate these stages, consider the electric grid system.

Stage 1 is characterized by total solar penetration being small enough ($<x_1$%) to be essentially ignored by the "system". This would probably be less than 5% total penetration of new solar. Although this is quite large from the Marchetti and Nakicenovic (1979) point of view, it is small in that there would be no question of system instability and solar plants would get almost full capacity credit no matter what the storage situation was. On a global basis, this amount of penetration would take about 30 years since global energy systems have a time constant of 50 years (1% to 50% penetration).

Thus, the first stage is mated to the existing conventional system and all back-up, storage and reliability requirements are provided by it. Some of the types of solar systems will have little or no storage, such as the solar thermal, photovoltaic and wind electric systems. The energy from these when configured as central solar systems will simply be put into the local electric grid. On-site systems would have excess energy pumped into the grid.

Stage 2 will have a total penetration greater than x_1% but less than x_2% so that the solar system's impact on the total system must be accounted for in some way. Some grid storage will be created in the form of pumped hydro (Weyss, 1976) and compressed air, but hybrid operation will be the rule. The conventional system will still provide the back-up, most storage and reliability functions and give the total system its stability and flexibility. Full capacity credit will not be assured for solar equipment, and grid reliability analyses must be performed carefully to avoid instability problems due to the greater solar presence.

The same family of solar systems will exist as in the first stage but some storage will exist via the grid in addition to the conventional fuels. There will still be no central hydrogen fuels, and x_2% will probably be about 15% to 20%. This should take another 30 years on a global scale. The remote central solar systems will be exceeding the local grids' ability to absorb their energy generation, and transmission links must be created to move the electricity and biomass fuels to other parts of the continent. D.C. electric transmission is most probable, as is biomass methane or densified biomass pellets.

Stage 3 will exceed x_2% but be less than 100%, and will be characterized by minimal fossil or conventional energy back-up, and the creation of maximum electric grid storage via underground pumped hydro and compressed air, as well as extensive use of biomass and seasonal heat storage.

The need for central hydrogen will be clearly in evidence and construction activities will begin in earnest. The central solar facilities will be expanded and hydrogen generation capability added. Pipeline links will be created and old natural gas pipline systems adapted for hydrogen use (primarily pumping station conversions). Underground hydrogen storage facilities will be created either by using depleted fossil fuel reservoirs, porous media or man-made underground caverns. Thus the construction of these central hydrogen facilities will be initiated but will not yet make any significant generation. The limit will be reached on the use of solar systems at other levels, as well as the amount of central electric storage that is required. x_3 should be about 35 - 50%.

Stage 4 will occur when x_3% of solar use is exceeded and central solar hydrogen starts to replace the role of conventional energy as back-up and storage, and insures the overall system stability and reliability. The end of stage 4 is this "eventual" solar system that provides 100% of societal energy demands.

With these stages of transition in mind, the macrosystem streamlining of this family of solar technologies can be considered. The four major energy system components are gathering, transport, storage and end-use. The family of solar technologies is vast compared with conventional energy technologies, not only with respect to the type of energy such as wind, hydro, roof collectors, biomass and desert power plants, but also with respect to the scale of any particular system. Biomass systems could be sized for a single home, such as biogas from animal wastes, or they could involve vast silviculture plantations producing woody material under optimized conditions. Even the same type and scale plant could produce a form of energy that is quite different. The silviculture plantation's woody product could be transformed into low, medium or high energy gas, depending on the location and nature of the end-user. Or it could be compressed into pellets with the handling and transport qualities of "western" coal. In addition, it could be used to generate liquids such as methanol or ethanol, or used in a conventional power plant to generate electricity. In turn this electricity could be converted into hydrogen. This variability of forms of energy is wide and many system configuration choices exist for each solar technology.

Another example is the solar thermal collector, which uses a parabolic dish as the key solar technology component. This device can generate heat for use in mid to high temperature (300 - 1200 °C) for industrial processes. Also, a small external combustion engine can be located at the focal zone to generate electricity at each dish. This modular approach can be used for applications from less than 10 kW(e) to as much as 1000 MW(e), simply by using the desired number of modules. Thus, on-site, community and central station electricity is possible. Also, low temperature waste heat is available for application nearer to the end-user. Thus one solar technology can have low to very high temperature heat, with or without electricity, from less than 10 kW to 1000 MW. To add further possibilities, hydrogen can be generated from the high temperature heat if small-scale thermochemical processes are available, or via electrolysis.

It is difficult to examine the macrosystem characteristics owing to the immense possibilities involved in arranging a solar system. However, one can observe that the intermittent nature of these varied solar resources do not occur with the same time phasing. In some areas, for example, wind is available when direct solar energy is not and this would tend to moderate the intermittent nature of the combined family of options. Also, the solar technologies are not being introduced into a void as the four stages described earlier point out.

When solar use reaches 10% globally, the existing energy mix will have from 0 to 25% nuclear, 60 to 80% gas and 4 to 10% oil use depending on the set of assumptions used. The dynamic system characteristics of this energy mix will certainly be stable. The use of solar at early penetration will directly substitute for other energy forms and provide a share of the energy use in most applications. 100% solar usage will tend to be rare initially at a particular site although such systems have been designed and lived in since 1972* where all energy requirements are met, including heating, cooling, cooking, electricity and even some transport.

One of the major sources of solar energy, biomass, has a built-in storage capacity, and excluding the central solar potential, biomass contributes about 1/2 of the total solar energy as shown in Table 1. Hydroelectricity has performance characteristics that allow some control on the rate of use, and it "acts" like storage to some extent. Also some solar options such as ocean thermal and SPS (orbital) can be described as having baseload characteristics. To the extent then that one could separate the family of solar technology from the overall mix of energy uses, they would appear to be more self-contained than at first apparent. However, this is essentially impossible to do analytically except with severely limiting assumptions.

For on-site solar systems, the gathering, transmission and end-use parts of the system are improved over other energy systems, since the sunlight is present itself at the site of the end user. The storage part of the system is usually not an improvement since a system with economically optimum storage will meet only 40% to 80% of the demand. Here the coupling with the existing conventional system would serve a back-up function to meet the remainder of the demand. As larger solar penetration takes place and some of the central solar techniques are developed, they would back-up the on-site systems.

When sited in sunny waste land, the central techniques would generate hydrogen as the primary energy carrier with some use of electricity if thermochemical water-splitting is not developed. If ocean deserts are used, then liquid hydrogen and possibly liquid ammonia could be used as the energy carrier to continental or island load centers. Hydrogen, especially in underground volumes, has excellent storage capability to lend system flexibility and stability. Even a hydrogen pipeline of

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*ILS Laboratories, Tijeras, New Mexico. Director: R. Reines.

1000 km has at least 10 hours storage itself. Electricity, which has limited storage capability in pumped hydro or compressed air facilities, would not be the problem one normally thinks. These central solar schemes are continental in nature and transmission links could be up to 1800 - 3600 km using high voltage DC. Feeding electricity to load centers spread over several timezones may ease load mismatching problems. Also, taking advantage of underground storage, hydrogen used to generate electricity using fuel cells could easily do whatever load-following is required.

Thus, the "awkwardness" of solar systems due to sunlight's intermittent nature and the need for storage, does not seem to be a difficulty when solar is considered as a complete system on a continental or global basis.

When the four major activities of gathering, transport, storage and end-use are considered, the solar "fuel" is delivered directly to the user for on-site and neighborhood direct solar systems. If storage is provided via a gaseous, liquid or even solid distribution system from central solar systems, these on-site and neighborhood systems are equal or somewhat superior to the natural gas or nuclear systems. If the solar equipment is considered in addition to the "fuel" itself as part of the macrosystem, the gathering, transport, and construction of this equipment is similar to any other industrial activity, and similar to the case for other, prior energy systems' capital equipment.

For central direct solar systems, the "fuel" is not delivered directly to the user, but is gathered in favored locations, and delivered via a pipeline or liquid tanker transport and distribution system to the user. This is similar to the natural gas or oil energy systems. The only difference is the substitution of solar favored areas for favored gas or oil field locations. If compared with a global nuclear-hydrogen system, central solar has very similar macrosystem characteristics. It may even be preferable since ocean island siting will not be necessary as it might be for the global nuclear system (Marchetti, 1975) and the solar central plants would be located on the continent of use.

Finally the renewable solar systems each have a different macro system characteristic. Biomass will be similar to coal, oil or natural gas systems depending on whether the energy form is solid (wood, charcoal, or compressed pellets), liquid (methanol or others), or gas. Other renewables such as wind and hydro depend on the size and scale used. OTEC will look more like the nuclear ocean island system. The resulting overall macro system characteristics of the particular mix of solar systems that might evolve is difficult to predict. But it is clear that many arrangements are similar to and in some cases superior to the energy systems that preceded it.

It was noted that the primary energy system transitions have gone to increasingly dense fuels, i.e., wood to coal, and coal to oil, etc. Also, each transition was marked by using fuels in an increasingly concentrated manner, i.e., coal trains to pipelines to nuclear fuel rods. Solar energy seemed to be going against these trends. Although this was touched on earlier, it was the transport and storage parts of the macrosystem where greater energy density was an advantage. However, for the on-site use of solar energy, there is no explicit transport of energy. Thus increased energy density is not a particular advantage of these systems in energy transport. Storage of hot water or electricty for on-site systems is another matter. For central solar systems, hydrogen and methanol would eventually be used with transport and storage characteristics similar to gas and oil today. With biomass type solar systems, it depends on whether the energy is transported and stored as solid, liquid or gas.

If one goes back one step further and looks at the area energy density of oil and gas in the ground, for example, spread over the continent, it is possible to compare this with the resultant energy density of solar energy on a continental basis. Based on estaimtes of 5300 to 250,000 bbl/mi^2 of oil and 360 to 1300 million ft^3/mi^2 of gas on a continental basis (Grossling, 1977), this results in an initial energy density of 75 to 304 kWh/m^2 based on ground surface area. If used evenly over 100 years, this results in a power density of 0.09 to 0.35 W/m^2.

When direct solar energy is considered to vary from 1000 to 3000 kWh/m^{2}yr, this results in 0.4 to 3.2 kWh/m^{2}yr energy density and 0.05 to 0.37 W/m^2 delivered power density continuously. This is based on 2% to 16% land availability applied to one-third of the total land, with 30% ground cover of this land at 20% efficiency to end-use energy. Using the simple average of these ranges, the total for oil and gas is 0.22 W/m^2 for 100 years and 0.21 W/m^2 for solar forever. At the resource level, this shows that solar has a similar power density to the combination of oil and gas. So the observation that solar energy is less dense than fossil liquids and gases is true and false depending on exactly what one is referring to. How important this is depends on how this characteristic contributes to system streamlining.

Therefore the solar system when taken as a whole has reasonable system characteristics, initially as part of a conventional energy mix, and eventually with biomass, hydro, seasonal heat and central solar with hydrogen, and possibly methanol as storage and back-up. The overall system streamlining characteristics in this case are the equal of the nuclear-hydrogen energy option if not superior because of some on-site and neighborhood capability. Thus, solar is roughly similar to the natural gas energy option used on a global scale, but has the vital characteristic of renewability.

Possible Cost Constraints

So far we have discussed whether solar is constrained by either fuel availability (insolation levels) or by difficulties in streamlining as a microsystem. The next question on our list is whether solar is inherently limited by its economics.

Central Solar Thermal Electricity and Heat

The central solar systems that generate electricity, and that could eventually be used for long distance electric transmission or for hydrogen generation via electrolysis, comprise the principal government R&D area of solar programs in the US and other countries. Most emphasis is being placed on the central receiver approach using two-axis heliostats (mirrors) to bounce direct beam insolation to a receiver placed on top of a tower. Here the heat is used either to generate steam for use in conventional steam (Rankine) turbine-generation equipment, or to heat a gas for conventional gas (Brayton) turbine-generation equipment. These approaches are straightforward extensions of conventional utility industry technology and simply substitute the heliostat field-tower for the fossil combustion or nuclear core heater.

Some consideration is also being given to using other fluids (such as liquid metals or high temperature salts like Hitec) in the receiver besides water-steam or gases. This can allow for higher temperatures for steam systems.

In addition to these central receiver approaches, dispersed collectors are being developed using one-axis tracking parabolic troughs of various designs, and two-axis tracking parabolic dishes with moving receivers as well as tracking reflectors.

Cost estimates for eventual solar devices (collector or heliostats) extend over a wide range owing to the prototype nature of the current situation. Figure 10 shows two corporate estimates of heliostat cost ($\$/m^2$) versus production rates and indicates some confidence that the US Department of Energy (DOE) $70\$/m^2$ goal is achievable. The more recent effort based on the General Motors collaboration with the US Solar Energy Research Institute (SERI) at Golden, Colorado, seems to verify these projections (Britt et al., 1979).

Transport, profit, and installation costs are estimated to add 17 to $20\$/m^2$ to these predictions of production costs. Thus the total installed cost is estimated to be $69.2\$/m^2$ at a production rate of 250,000 units per year per plant (Britt et al., 1979) in 1975 dollars. This is similar to the production capacity in automobile plants and represents about 2.5 GW peak capacity per year.

Based on an extensive study of some of the possible systems just mentioned (Fujita et al., 1977; Caputo, 1981; Doane, 1976), a range of *system* capital and energy costs is presented in Figure 11 for electricity and for high temperature (~500 °C) heat. The more expensive edge of the range is for nearer term technology (central receiver with steam generation and coloria/rock storage and Rankine turbine-generators) with heliostats at twice the DOE cost goals ($\sim 145\$/m^2$) and a system efficiency of 19% including dry cooling techniques (no cooling water). The less expensive edge of the range is for more advanced

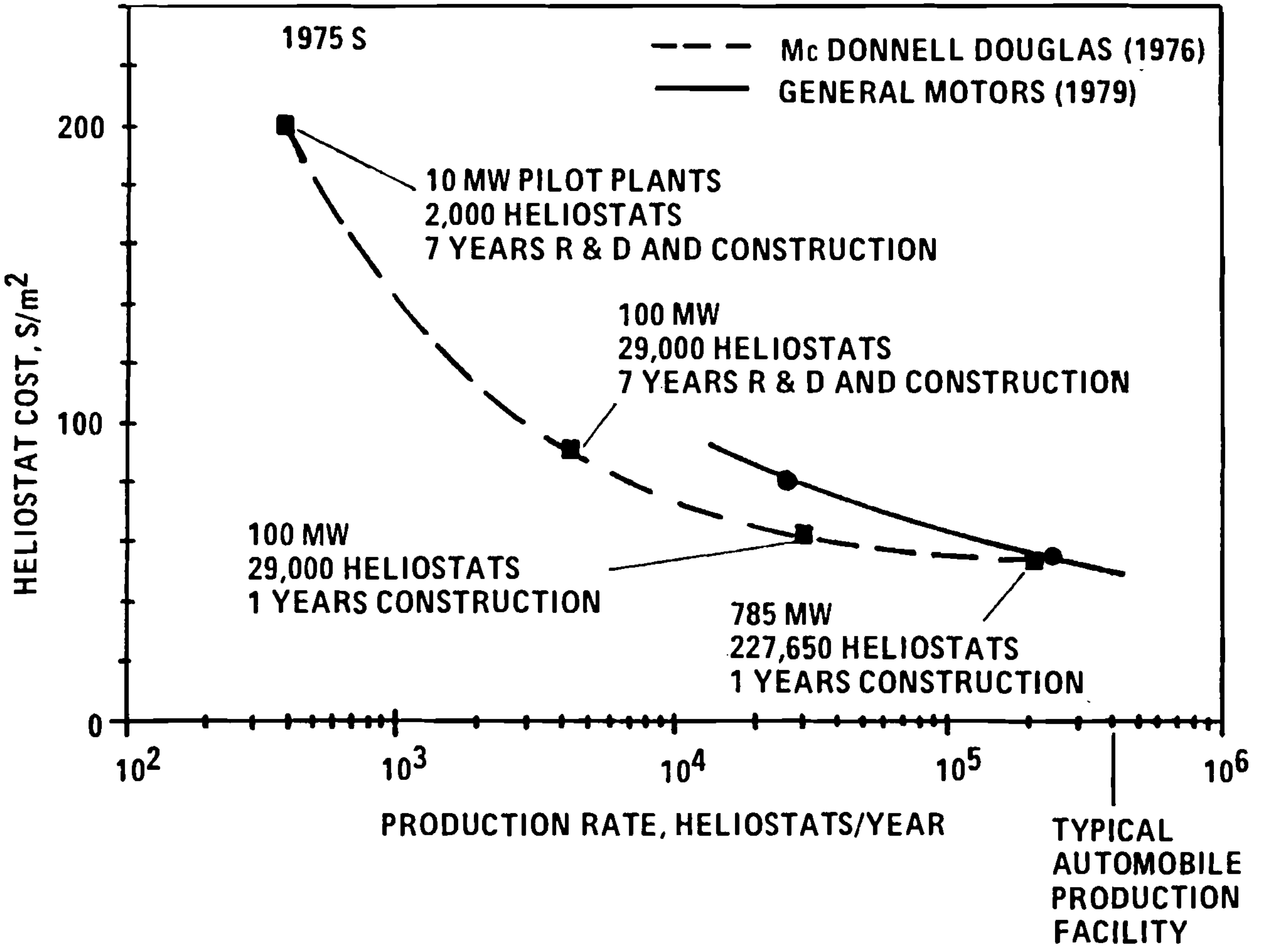


Figure 10. Heliostat production rate projections. For McDonnell Douglas see also Häfele (1981); for General Motors see Britt et al. (1979).

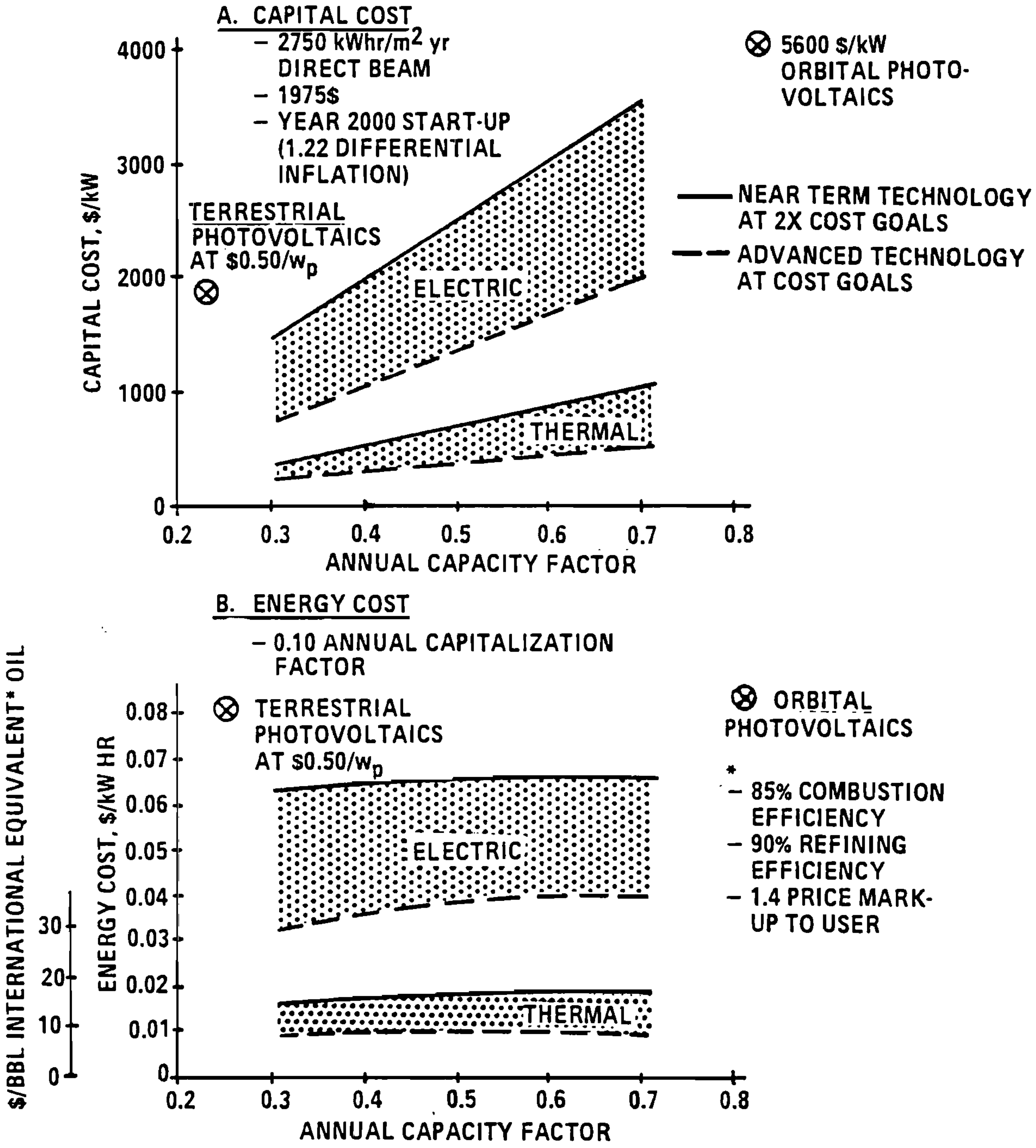


Figure 11. Solar power plant costs.

technology. An example would be a parabolic dish with high efficiency Stirling engine-generator mounted at each receiver, or a 1000 °C ceramic receiver powering a combined cycle gas and steam turbine. These advanced systems would be at the DOE collector cost goal of 70 - 110$/m^2 depending on the technology, and a typical system efficiency would be 27%. Located in good sunny waste lands with 2750 kWh/m^{2}yr insolation, the generated electricity cost is from 0.032 to 0.063$/kWh using 1975 dollars, a 0.10 annual capitalization factor, and a capacity factor of 0.31. Included in the calculated cost is a multiplier of 1.22 to account for differential inflation to the year 2000 based on US data (Caputo, 1977). (That is, if the hypothesized plant would cost 1230$/kW(e) for completion in 1975, it is considered to cost 1500$/kW(e) (1230 × 1.22) in 1975 dollars if constructed in the year 2000.) The 0.10 annual capitalization factor is used for convenience and consistency with similar calculations in Häfele (1981). Private utilities would use a factor closer to 0.20 (Doane, 1976) to account for interest on borrowed capital, insurance, taxes, profit, etc. For public utilities the number is closer to 0.15. Also included in calculating the electricity cost is an operation and maintenance account that ranges from 1.14 (near-term) to 1.24 (long-term technology) times the capital cost. The 1.24 factor accounts for the higher maintenance cost of the Stirling engines assumed in the advanced system.

It should be noted that capital cost increases nearly linearly with annual capacity factor up to about 0.70, while energy cost is essentially constant. Costs increase more rapidly above 0.7 capcity factor. Storage costs are estimated to be from 30 to 60$/kW(e)h.

Simplified estimates of conventional baseload plant costs are shown in Figure 12 for comparison. Oil, coal and nuclear electric plants are shown with the most uncertain factor for each considered as a variable; these are respectively oil price, coal price, and nuclear capital cost. Thus, according to the figure, at an international oil price of 30$/bbl, the cost of electricity at an oil burning plant (busbar) is 0.075$/kWh. Or for a coal plant at a capital cost of 1000$/kW(e) and using 50$/ton coal, the plant electricity cost would be 0.034$/kW(e)h. However, a coal plant with suitable sulfur removal techniques is estimated to cost 1300$/kW by 2000 in 1975 dollars (Caputo, 1977).

In the case of nuclear power a little more elaboration is necessary. In most of the world, but especially in the US nuclear installed costs have been escalating at rates greater than general inflation by up to 10% per year (Atomic Energy Commission, 1974; Bupp et al., 1974; Montgomery and Quirk, 1978). One estimate of the year 2000 start-up cost of a nuclear power plant (Caputo, 1977) is 2200$/kW(e) in 1975 dollars, with a wide uncertainty band of 1300 to 2800$/kW(e). This continued differential inflation is due in part to a persistent adverse societal resistance to nuclear power.

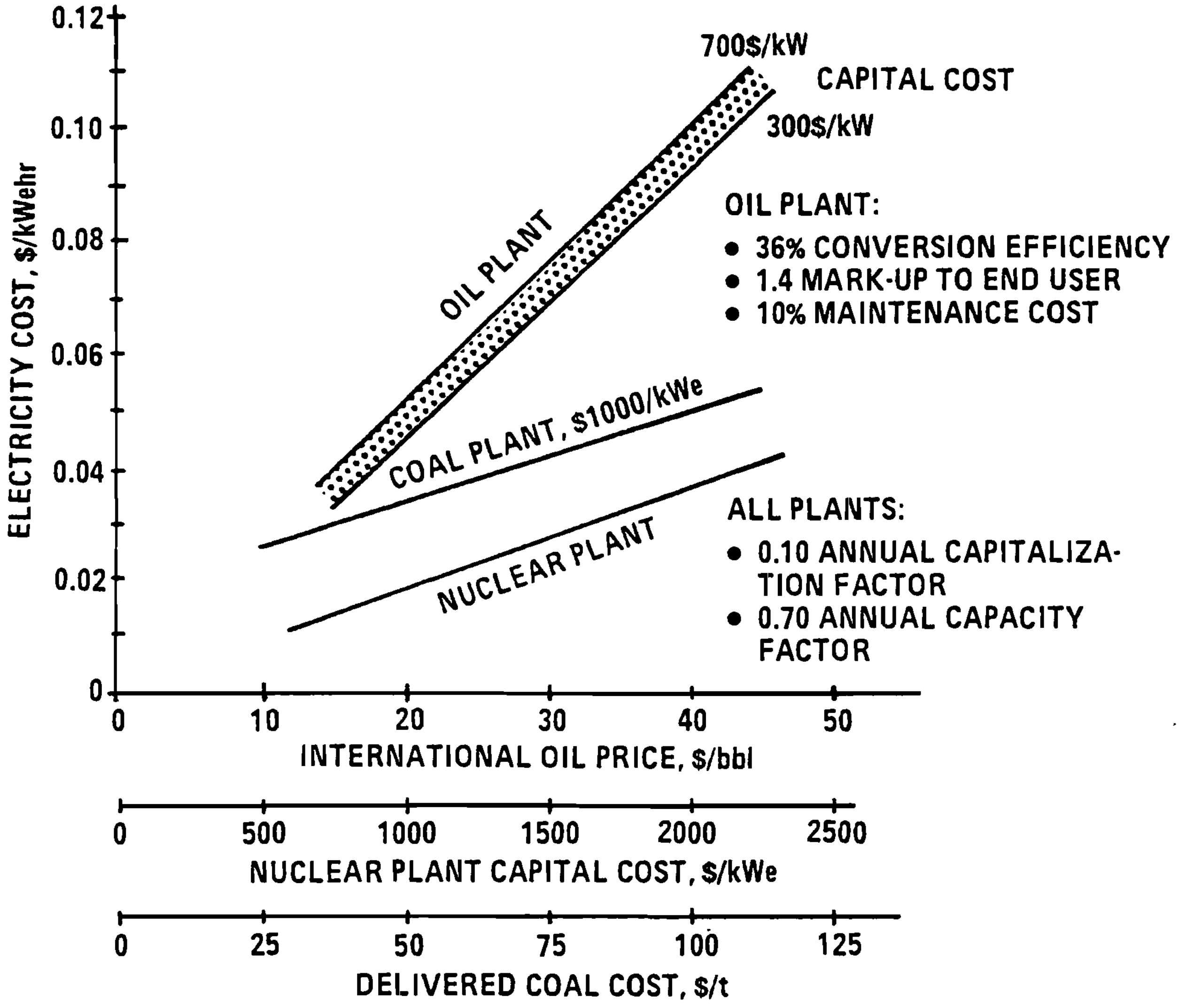


Figure 12. Conventional baseload electric plant cost.

In the US, which recently had a two-year moratorium on new plant construction, this social resistance has been translated into costs via several institutional mechanisms such as the required environmental impact statement and required hearings, which lengthen construction time from about 5 to 12 years. This process increased construction financial charges from about 10% to over 40% of total installed cost (Montgomery and Quirk, 1978). Also for various subsystems, such as heat rejection and radioactive emission, the required design specifications have evolved over time and increased costs. Major uncertainty currently exists as to the type of future requirements and their impact on cost. Examples of possible future mechanisms through which social resistance might be translated into system cost are underground or more remote siting (Terasawa et al.,1978), including deactivation (decommissioning) costs in initial costs, requiring private insurance against nuclear accidents, and including long-term waste disposal costs in initial costs, etc. In addition, some countries and several states in the US are insisting that certain requirements such as the designation of long-term waste disposal techniques be met before a nuclear plant is approved. This in effect allows nuclear energy penetration only on the condition that some socially perceived cost is successfully internalized.

Breeder cost projections are about 25% more than the LWR system. However the real competition for solar power is the breeder reactor since the continued use of burner reactors would result in "yellow coal" uranium. That is the ore grades of uranium would become quite poor and the bulk handling of uranium ore would approach coal in magnitude. This makes the pricing of the competition to solar even more difficult since breeder reactors are in the prototype stage and there are the usual difficulties of commercial projection of prototype equipment, as well as the enormous vagaries of the social acceptance of breeder nuclear technology. The US has put an indefinite postponement of the breeder prototype program, but France and West Germany seem to be proceeding.

With these remarks as background, Figure 12 shows for nuclear power, for example, that the busbar electric cost would be 0.040$/kW(e)h using the 0.10 annual capitalization factor at 2200$/kW(e) installed cost. Current installed costs are close to 1000$/kW(e) in 1975 dollars and this is about 0.020$/kW(e)h.

Looking at Figure 6, early solar technology at even twice the US DOE cost goals appears competitive with oil-fired electricity at today's international oil price. The more advanced version of the solar electric plant would be competitive with nuclear and coal electricity around the year 2000 if the future cost estimates cited above from Caputo (1977) prove to be accurate, and the solar plant is sited in a sunny wasteland (insolation of 2250 kWh/m^2yr). However, the solar plant will probably be more in the middle of the range indicated in Figure 11B, thus leaving solar in a less competitive position with respect to coal and nuclear until after the year 2000. In the case of nuclear, however, we again note that the major question surrounding nuclear plant availability is social acceptability rather than projected energy cost.

So far in this section, we have not considered questions of utility grid reliability, back-up, multiple solar plant siting with different insolation patterns, the type of electric grid, load patterns, or storage other than a fraction of a day. However, a conservative estimate (Caputo, 1977) was made of solar electric plants in a specific utility grid (Southern California Electric), functioning as baseload plants (not an early application) at one weather site, with an annual capacity factor of 0.7 with 7 hours storage. Back-up installed capacity of 30% of solar rated power was calculated to be required to make the grid as reliable with solar plants was without. This added about 15% to the installed capital cost. No back-up energy was required if a 0.7 capacity factor was suitable for baseload plants.

Central Solar Hydrogen

Early solar electric plants would most likely be fuel savers operating in a hybrid fashion in either existing fossil power plants (repowering) or in new plants. Major initial forcing factors to introduce solar electric plants would be the desire to replace expensive fossil fuel or perhaps the need to gain public acceptance for siting a new power plant by hybridizing it with solar. Eventually, as solar penetration exceeded ~10%, some grid storage would be introduced using pumped hydro and compressed air systems. As fossil fuel gave way eventually (~50 years) to solar-generated hydrogen, the hydrogen would provide the back-up and load-matching function via easy storage in underground volumes. Fuel-cells or efficient heat engines (Stirling) used on-site or in neighborhoods with use of waste heat would probably be the electric generating system fed by this pipeline hydrogen.

Using solar plants in sunny waste land regions, the cost of generating hydrogen is shown in Figure 13. Using the same range of technology and cost shown in Figure 11, the solar electric electrolysis approach will cost between 0.037 and 0.056$/kWh of hydrogen energy. If thermochemical splitting of water is developed commercially at about 500$/kW and 60% efficiency (Bockris, 1975), the total solar to hydrogen energy cost would reduce to 0.020 to 0.050$/kWh. This is equivalent to 34 to 82$/bbl for international oil. The 1.22 cost multiplier is used throughout for solar plants to account for differential inflation to 2000.

For comparison, the cost of hydrogen from coal is also shown in Figure 13. For coal at 100$/ton, hydrogen would cost 0.035$/kWh, which is equivalent to oil at about 60$/bbl. This is based on Kim et al. (1979), who suggest 700$/kW capital costs and a 62% coal to hydrogen efficiency. As shown in Figure 13, the hydrogen from coal cost range represented by 50 to 150$/ton

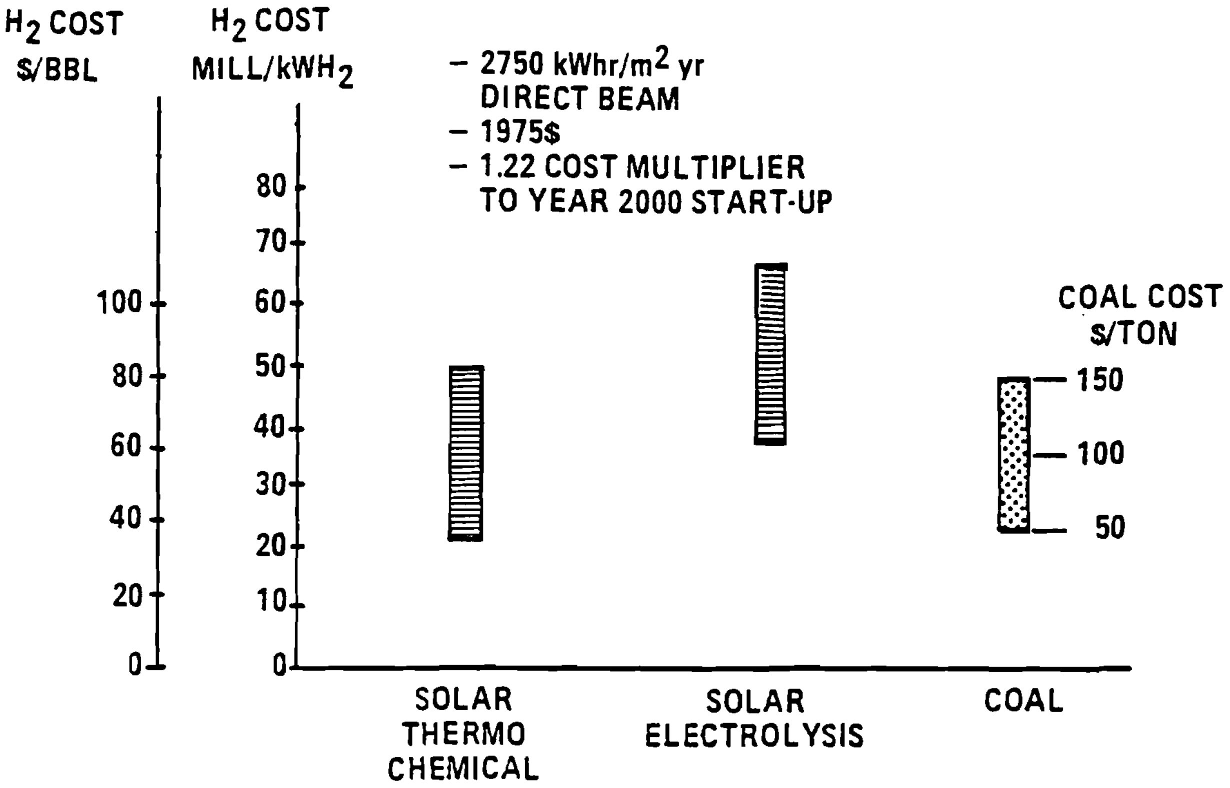


Figure 13. Hydrogen generation cost.

coal is essentially the same as the expected cost range of solar thermal hydrogen, and overlaps the solar electric hydrogen.

Central Solar Methanol

Methanol (CH_3OH) may see a role as an energy carrier as either a ground transportation substitute for oil or as a non-grid energy source or back-up energy source. The cost of methanol from solar electric hydrogen combined with coal as the carbon source is shown in Figure 14. About half the methanol energy is derived from solar hydrogen and half from coal. Both solar electric hydrogen and solar thermal hydrogen are shown. For comparison, an estimate is shown for methanol production directly from coal.

At 100$/ton for coal, the solar-coal methanol should cost from 43 to 68$/bbl if solar electric hydrogen is used. If thermochemical splitting is achieved, then the expected cost range reduces to 30 - 54$/bbl of oil equivalent. From coal directly, methanol would cost about 42$/bbl at 100$/ton coal. Thus solar-coal derived methanol would be competitive with oil at roughly double today's international price, especially if thermochemical splitting was commercially available. Biomass could replace coal as the source of the carbon atom for an all-renewable approach to methanol generation. This biomass could be produced from agricultrual and forestry wastes as well as woody plantations. It could be combined with solar hdyrogen to produce methanol with a more efficient use of the biomass carbon.

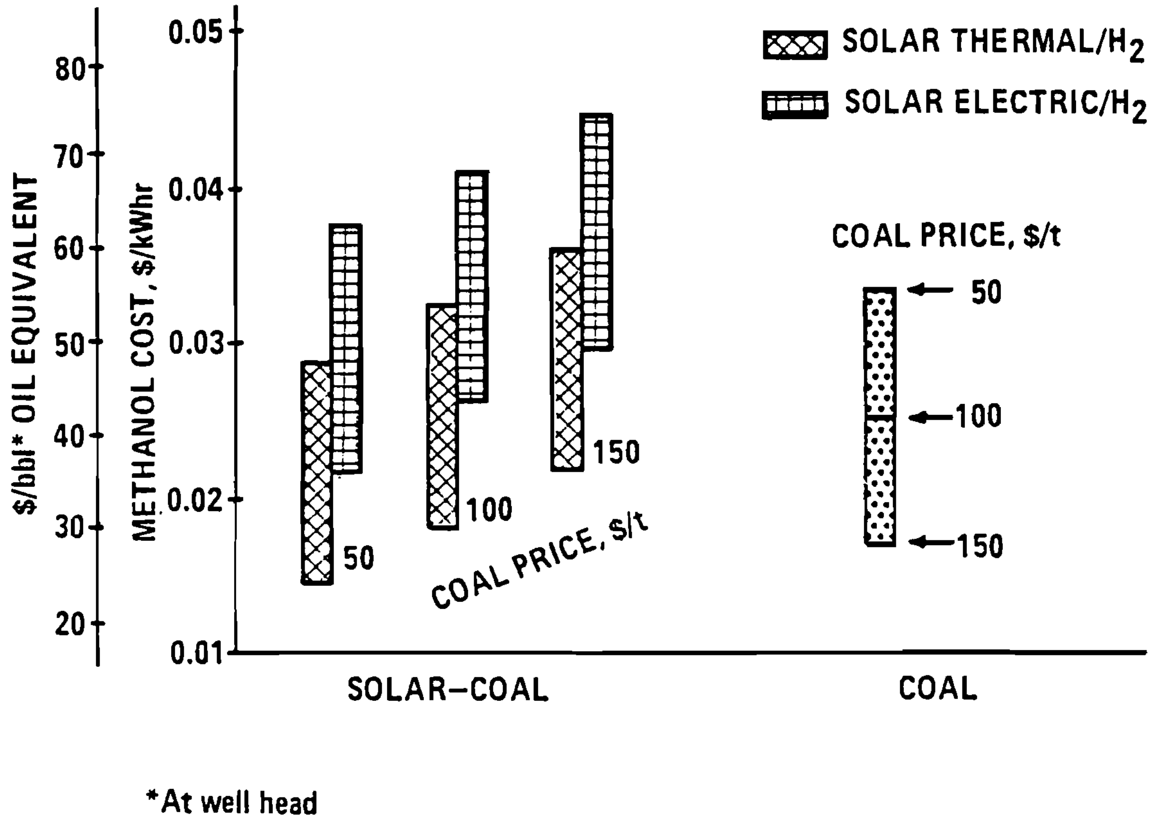


Figure 14. Methanol generation cost.

On-Site and Regional Solar

Electricity

On-site or regional solar electricity generation has the advantage of involving lower transmission and distribution costs than central solar generation. However, the central systems discussed above are assumed to be located in sunny waste lands and have therefore a compensating advantage of better insolation over on-site regional systems in less favorable climates. In comparing regional and on-site generation to central generation, we are therefore interested in the breakeven insolation level for the regional and on-site systems. That is, at what insolation levels are the savings in the transmission costs for a given amount of energy exactly balanced by the additional expense required to generate the same amount of electricity at the reduced insolation level rather than at 2750 kWh/m^{2}yr (the insolation in sunny waste lands)?

In order to calculate breakeven insolations we must first estimate the cost of the long distance transmission by high voltage DC and hydrogen pipeline that would be needed to deliver sunny waste land electricity or hydrogen to load centers several thousand km away. Caputo (1977) estimates that DC transmission of 3000 km would cost about 300$/kW in 1975 dollars at an efficiency of 96.5%. This would add about 0.006$/kW(e)h or 12% to plant generated (busbar) electricity costing 0.050$/kW(e)h. Electric distribution is estimated to add another 0.006$/kW(e)h (Caputo, 1977).

Transmission of energy using hydrogen would cost only 0.002$/kWh for 3000 km (Beghi et al., 1972), but the conversion of electricity to hydrogen if electrolysis was used would cost about 0.009$/kWhr. If this hydrogen is to be converted back to electricity at end use, this would cost 0.033$/kW(e)h even if 70% efficient fuel cells costing 300$/kW(e) were used.

However, waste heat can be used from on-site or neighboring fuel cells and if this heat is priced at the equivalent of 20$/bbl international oil, then the conversion back to electricity would only cost 0.022$/kWh instead of 0.033$/kWh.

These system possibilities are shown in Figure 15 starting with solar electricity at the average cost from Figure 5 (≈0.050$/kW(e)h). Although hydrogen transport is six times less expensive than DC transport and AC distribution, the delivered electricity cost is 0.094$/kW(e)h using hydrogen transport compared with only 0.062$/kW(e)h using electricity transmission. The difference is due to the cost of conversion to and from hydrogen. Delivered heat from hydrogen combustion would be equivalent to electric resistance heating at about 0.062$/kW(e)h. Even if all the waste heat from the fuel cell is used and sold at the equivalent of 20$/bbl (0.026$/kWh) the electricity cost only drops to 0.083$/kW(e)h. Therefore, to the extent that the central solar electricity generation overlaps the electric demand,

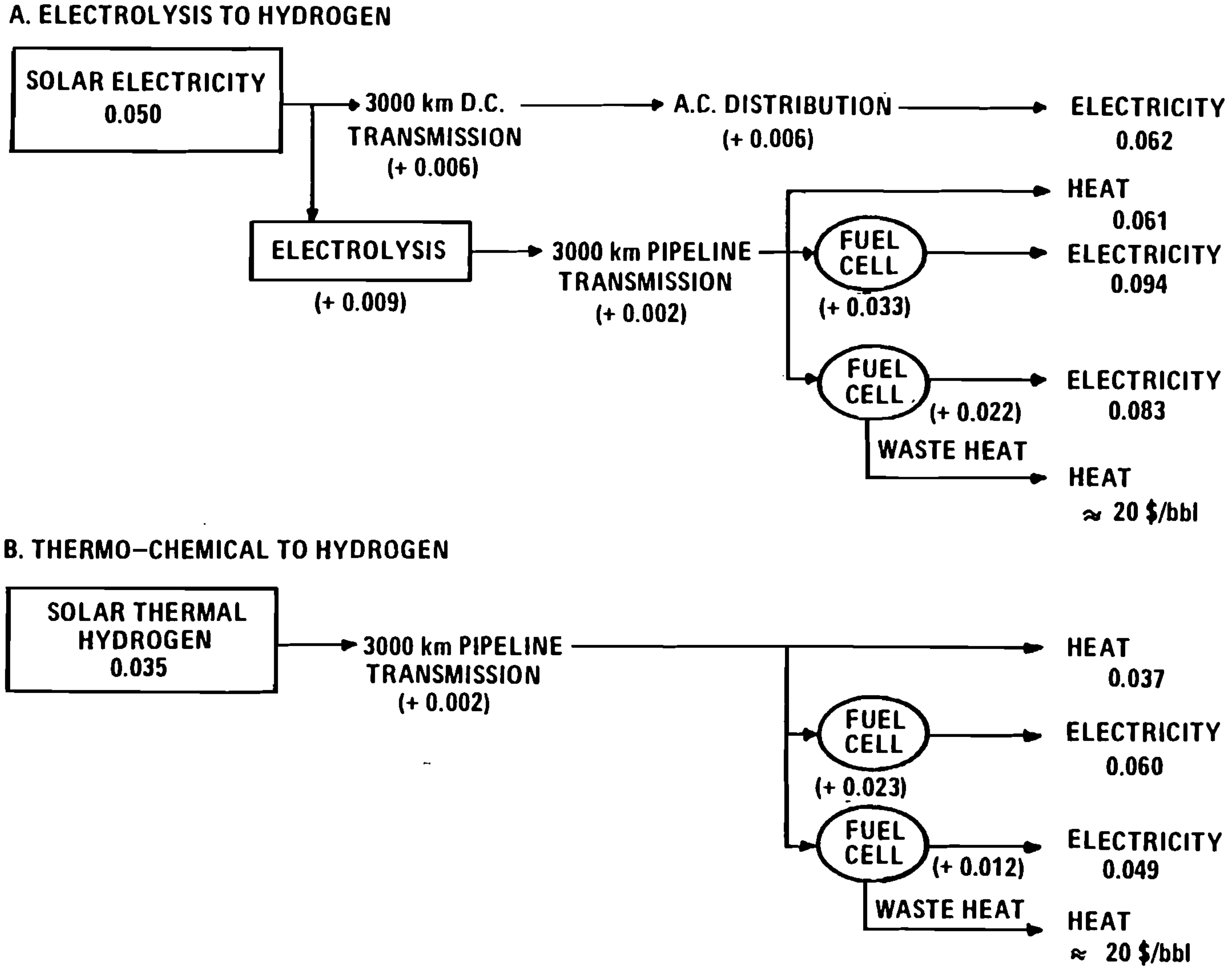


Figure 15. Delivered energy cost from central solar plants, $/kWh

electric transport is desirable. This electricity can be backed up by hydrogen fuel cells along with pumped hydro or compressed air storage to provide the necessary load following.

Beyond the question of relative economics, the environmental and visual impacts of electric transmission and hydrogen pipeline transmission are certainly different. Moreover, a ±800kVA DC overhead transmission line has a capacity of approximately 10 to 15 GW(e), while a 2 m diameter hydrogen pipeline can transmit 35 GW_{H_2} (a 3 m diameter pipeline transmits 100 GW). It may well be these characteristics rather than economics that are decisive in determining the type of transmission system used.

If thermo-chemical hydrogen is developed, then pipeline transmission will be used for central solar hydrogen. The delivered heat would cost about 0.037$/kWh (the average value shown in Figure 9), which is equivalent to international oil at 28$/bbl. Delivered electricity is 0.049 to 0.060$/kWh depending on the amount of waste heat used and its price. Figure 15 summarizes these general solar systems and delivered energy costs.

To get a rough estimate of the cost of regional solar electric one may simply ratio the cost inversely to direct beam insolation. Thus a solar plant achieving 0.050$/kW(e)h cost at an annual capacity factor of 0.50 in an insolation of 2750 kWh/m^2yr (see Figure 11) would cost approximately twice this if placed in half the direct beam radiation. This approximation is substantiated by Latta et al. (1979).

For example, insolation typical of Spain (Almeira) would generate electricity at about 0.060$/kW(e)h rather than 0.050$/kW(e)h of Northern Africa. The same plant in southern Italy would generate electricity at about 0.070$/kW(e)h, and in southern France (Odeillo) at 0.080$/kW(e)h. These calculations are based on insolation data in Lof et al. (1966) and Landsberg (1970).

To get the breakeven regional insolation for each of the central solar technologies discussed above, we simply reversed the calculation. We started with the cost target needed for regional generation to be competitive with central generation. Then after accounting for the distribution costs associated with a regional system, we found the breakeven insolation level such that the ratio of desired regional generation costs to generation costs in sunny waste lands equalled 2750 kWh/m^2yr divided by the breakeven insolation level. The results are shown in Table 2. Table 3 lists insolation levels in different areas of the world.

On-site heating clearly can compete favorably with central systems, and in this case central systems would only be needed for back-up. However if advanced designs at cost goals are achieved, regional solar electric systems at insolation of

Table 2. Comparisons of central and regional solar

Breakeven regional* direct normal insolation (kWh/m^{2}yr)						
advanced at goals		near term	Delivered central solar energy ($/kWh)	Delivered energy form	Central solar plant type	Transmission
1800	-	3150	0.062	electricity	electric	electricity
<1000			0.061	heat	electric	hydrogen
1360	-	2350	0.083[1]	electricity	electric	hydrogen
1200	-	2100	0.094[2]	electricity	electric	hydrogen
<1000	-	1250	0.037	heat	thermal	hydrogen
2300	-	4000	0.049[1]	electricity	thermal	hydrogen
1900	-	3250	0.060[2]	electricity	thermal	hydrogen

* Regional solar electric system is considered to have short distance (~200 km) AC transmission and distribution cost of 0.009$/kWh included.

[1] on-site fuel cell, 100% sale of waste heat at ~20$/bbl.

[2] on-site fuel cell, zero sale of waste heat.

Table 3. Solar radiation as an energy resource. Based on Weingart (1978).

The solar constant	1353 W/m^2
Effective radiation temperature of the sun	5760 K
Maximum direct normal irradiation at sea level	~1000 W/m^2

Region irradiance		kWh/m^2-day	kWh/m^2yr	W/m^2 (average)
Monthly average direct beam radiation in sunny, arid regions		5-10	1825-3150	210-420
Average annual direct beam irradiance in sunny regions		7-8	2550-2900	290-330
Tropics, deserts	Annual average horizontal global	5-6	1800-220	210-250
Temperate zones		3-5	1100-1800	130-210
Less sunny regions (e.g., Northern Europe)		2-3	700-1100	80-130

<1360 kWh/m^2yr are competitive only with central solar electric plants with hydrogen transmission. Only the best regional location (>1800 kWh/m^2yr) could compete with central electric plant with DC transmission even if cost goals are achieved.

If the regional system is on-site (no transmission and distribution) the required break-even insolation is reduced by about 20%. This improved the on-site competitiveness and considerably extends the favorable areas.

Industrial process heat

In addition to electricity, industrial process heat can be generated by concentrating solar collectors. The range of technology/cost used in Figures 11, 13 and 14 are shown in Figure 16 as the two lower cost curves. A third case is shown which is close to systems currently available in the US using existing technology. The delivered cost of heat is shown versus available direct beam radiation. At 1300 to 1700 kWh/m^2yr typical of good southern Europe locations, delivered heat would cost 0.015 to 0.040$/kWh depending on the system utilized.

For comparison, the equivalent international oil price is shown. The nearer-term technology at twice the cost goals is

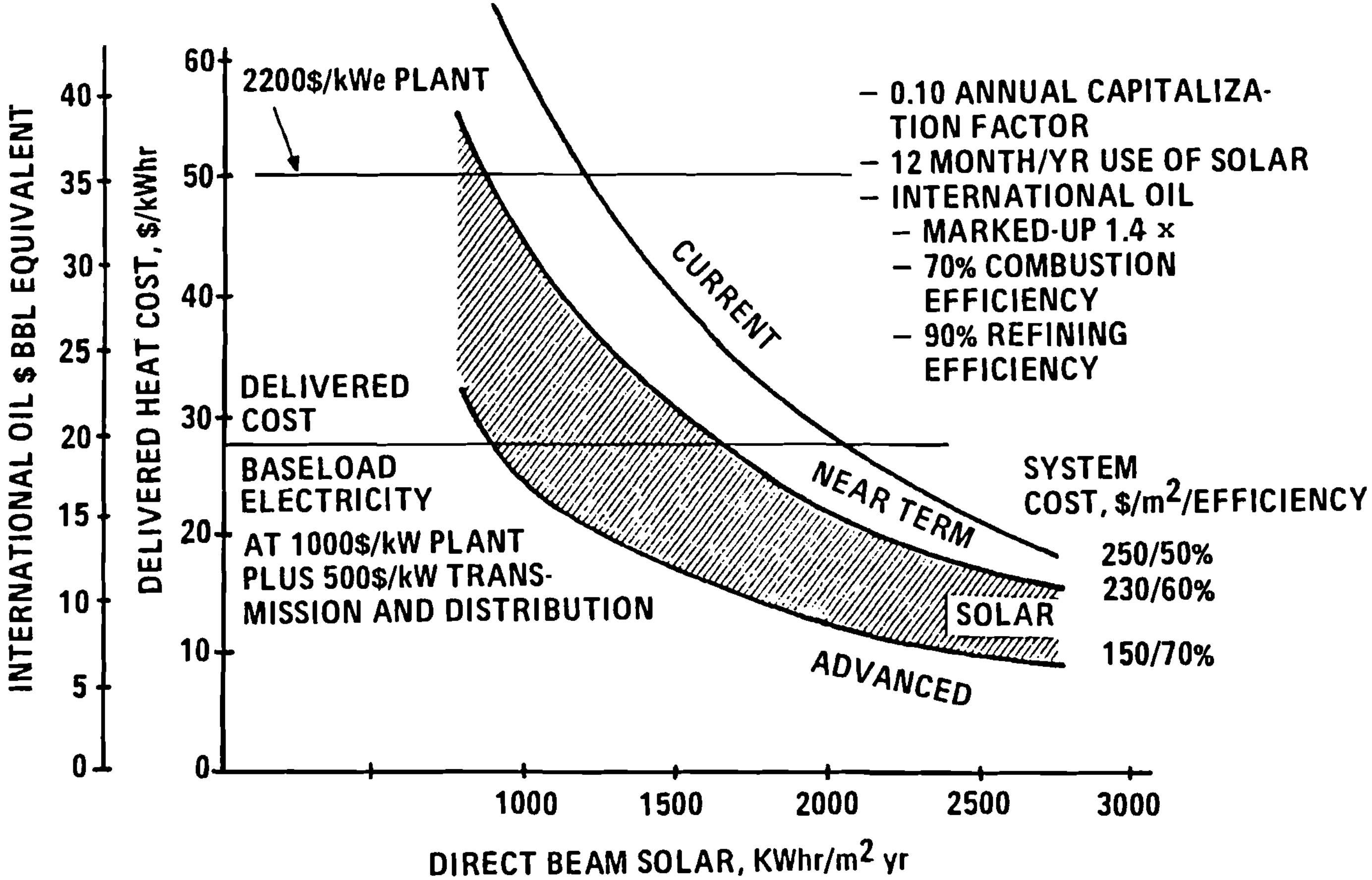


Figure 16. Higher temperature solar heat cost.

competitive with 30\$/bbl oil at an insolation of 1100 kWh/m^{2}yr which is exceeded by a good deal of central and southern Europe and almost all the US. Also shown is the cost including transmission and distribution of delivered nuclear baseload electricity at current cost of 1000\$/kW and projected cost of 2200\$/kW(e). Again solar heat is quite competitive.

Questions of storage and back-up exist, but, as discussed, first fossil sources then solar hydrogen and/or methanol would form the complete system and would have good system stability. Hydrogen from the most advantageous system considered is 0.021\$/kWh (from Figure 9) plus 0.002\$/kWh for pipeline delivery. On-site solar heat can be produced at this cost with similar equipment if the direct beam insolation is equal to or greater than 1100 kWh/m^{2}yr direct beam.

Low temperature heat

Lower temperature heating can be achieved with fixed flat collectors capturing both direct and diffuse radiation. Figure 17 shows the estimated cost of low temperature solar heat based on an installed system cost of 225\$/m^2 and 40% system efficiency. At 1250 kWh/m^2 total insolation on a tilted fixed surface, the heat cost is 0.50\$/kWh. This is competitive with delivered baseload nuclear electricity at 1850\$/kW plant cost and international oil at 30\$/bbl. By reference to Figure 12 including the electric delivery cost, this is competitive with baseload coal at 40\$/ton. At 2000 kWh/m^{2}yr (Los Angeles), the solar heat is less expensive than both nuclear power and international oil current costs.

If compared with central solar hydrogen at the middle of the range associated with solar-thermal-chemical from Figure 13 (0.035\$/kWh plus 0.002\$/kWh for transmission), the on-site insolation should be about 1700 kWh/m^{2}yr to be competitive. If the mid-range of the solar-electric hydrogen is considered (0.05\$/kWh) plus 0.012\$/kW for delivery, then about 1000 kWh/m^2 is the breakeven insolation for on-site competitiveness.

If, however, we assume that only 40% of annual local insolation is available for solar winter heating for buildings, the breakeven insolation increases to 4250 kWh/m^{2}yr to be competitive with solar thermochemical hydrogen and to 2500 kWh/m^{2}yr to be competitive with solar electrolytic hydrogen (see Table 4).

These results indicate that a 12 month/year on-site heating application is able to compete economically with central solar electrolytic hydrogen almost anywhere, and with central solar thermal hydrogen in favorable locations (>1700 kWh/m^{2}yr). Winter season on-site heating with active collectors cannot compete with any central solar system. Such competitive on-site solar systems would therefore require back-up and would probably provide from 40 to 80% of the annual energy requirement depending on site specific factors such as the interaction between weather, insolation and user characteristics.

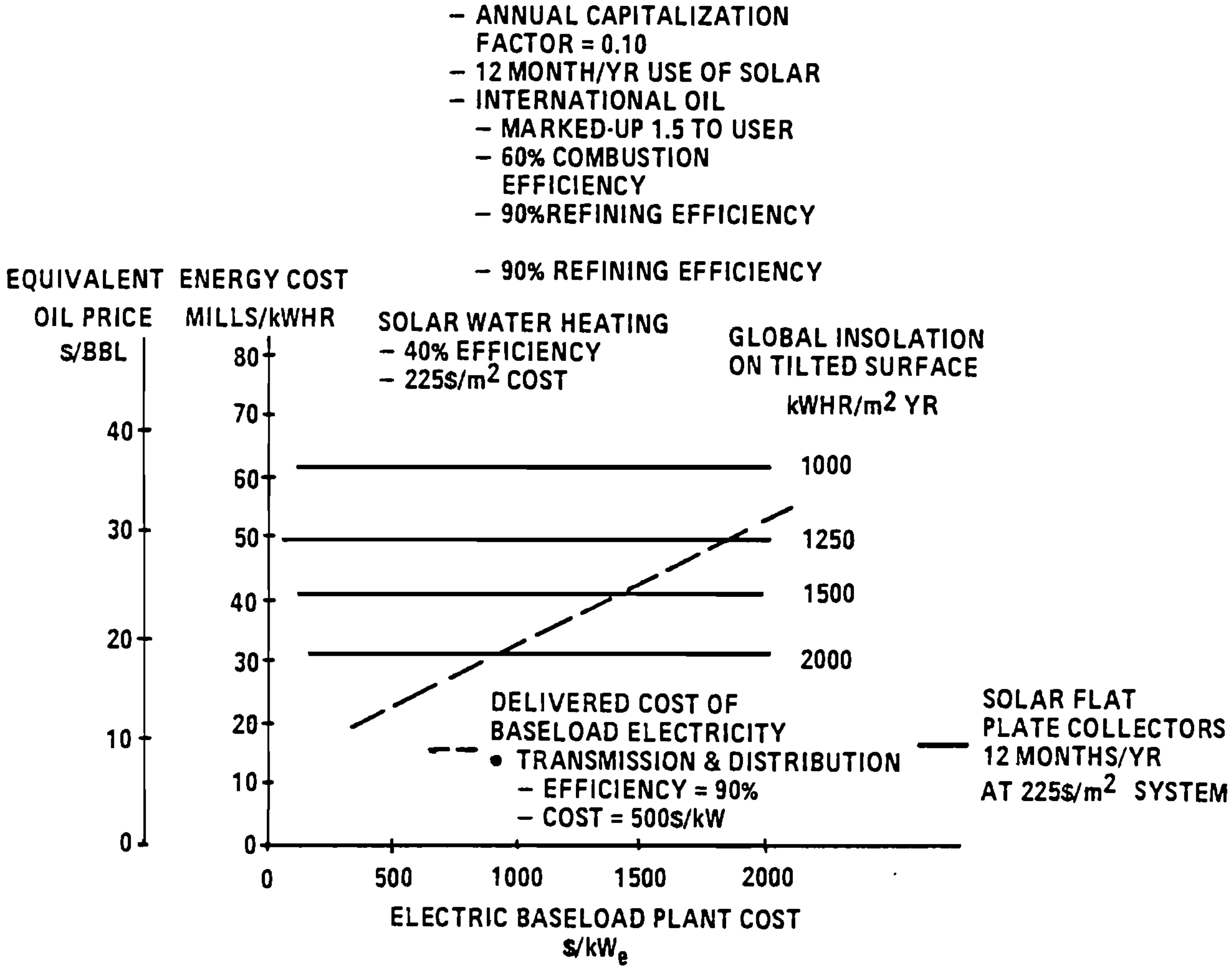


Figure 17. Low temperature solar heat cost.

Table 4. Local insolation required to compete with central solar (kWh/m^2yr).

	On-site solar heating	
Central solar	Seasonal heating	Year-round
Solar electric hydrogen	2500	1000
Solar thermal hydrogen	4250	1700

The above breakeven calculations, however, neglect several factors that might make on-site solar more competitive. For example, if consumer labor and indigenous materials are used, the on-site systems may be less expensive than commercial systems even on a per unit energy delivered basis. If a cost improvement by a factor of 2 is achieved using this approach, it would halve the local insolation required to be economically competitive with energy from central solar. Thus application of local solar systems for 12 months in a year would be competitive against central solar, whether solar electric or solar thermal hydrogen. In addition, seasonal solar heating would be competitive in most locations against central solar electric hydrogen.

A comparable consideration is the adoption of passive heating and cooling techniques, which promise to be similar in cost to conventional housing construction. When passive techniques become commonly available and overcome the usual barriers associated with anything "different" in the building industry, they can also provide 40% to 80% of space conditioning needs (both heating and cooling) at little if any additional cost. By passive techniques we are referring to such things as: heavy south wall (Trombe wall) with or without glazing, attached green house, roof water bags with variable cover and direct gain in south face using properly sized windows, internal mass in floors and night time variable insulation.

Solar systems can also be advantageously combined with electric heat pump systems. The heat pump extracts energy from a heat source that is usually ambient air, and thus usually does not work effectively in colder climates where winter ambient temperatures are below 0 °C. Solar flat plate collectors could heat water to modest temperatures (<50 °C) thus providing an attractive heat source for the heat pump and allowing much more efficient use of the electricity. For such a low temperature application relatively inexpensive and simple collectors, possibly using plastic at half the system cost, could be used.

A special case arises for remote or island sites. Here on-site systems are competing with central solar hydrogen delivered not through a pipeline network, but via some sort of liquid transport link, since liquid transport is less efficient than pipeline transmission. On-site systems in such locations would need only 70% of the breakeven insolations of Table 4 to be competitive owing to the 70% efficiency from gaseous to liquid hydrogen.

The use of on-site and smaller-scale solar systems involving neighborhoods and villages or other types of commercial groups will find greater than expected use if lifestyle factors are important compared to relative economics. Systems that favor more local control, and more local involvement in construction would find surprising use if social values make these characteristics important compared to monolithic, central systems.

Finally, seasonal storage of heat would allow summer time collection for use during the heating season. Current development work is promising and may extend the competitiveness of on-site solar (Margen and Roseen, 1979).

Cost Summary for Solar Thermal Technologies

Before moving on to photovoltaic applications, we have summarized in Table 5 the cost estimates that we have just discussed. To the extent that the dominant decision making criterion is economics in the form of levelized energy cost over the life of the energy equipment, the following conclusions may be reached.

For central, regional or on-site installations, solar electricity is competitive with oil-generated electricity. Favored site solar electricity is relatively unattractive compared with coal-fired baseload electricity until coal costs about 100$/ton and installed nuclear plant cost exeeds 2000$/kW(e). (Current coal cost in Western Europe is about 100$/ton in 1975 dollars.)

Thermochemical splitting of water will enable advanced and low cost solar thermal systems to compete with hydrogen generation from 50$/ton coal. Not achieving this will reduce solar competitiveness to 100 - 150$/ton coal. If, as a long-term pricing strategy, coal is assumed to be priced at 70% of the international oil price, then coal will be priced at 100$/ton when oil is 28$/bbl. A similar statement can be made about methanol generation.

High temperature solar heat will be competitive with oil and electric resistance heating, and also with coal when coal reaches about 100$/ton. If a high temperature thermal application can be located at a nuclear reactor that has a sufficiently high temperature capability, then the nuclear heat would be roughly twice as cost effective as solar at a central site. Remote siting of nuclear facilities would dilute this advantage.

Table 5. Summary of solar cost estimates (0.10 annual capitalization factor, 1975 dollars[1], $/kWh × 1000[2])

		Conventional costs[4]		
Application	Solar cost[3]	Oil	Coal	Nuclear[9]
Electricity				
central[5]	38-65[6]	75[7]	34[8]	28
regional[5]	60-105[10]	75	34	28
on-site	72-150[10,11,12]	96[13]	50	43[13]
Hydrogen[5,6]	20-50[14]		23[8]	
	36-67[15]		35[16]	
			48[17]	
Methanol	18-33[14,16]		25[16]	
	26-41[15,16]			
Heat				
high temperature		33[7]	10[8]	7[18]-43[19]
central[6]	10-18			
regional[10]	15-28			
low temperature[23]		50[7]		43[19]
all year-round	31-62[20,21]			
winter only[22]	78-155			

[1] 1.22 cost factor is included in solar equipment to consider differential inflation to the year 2000.

[2] $/kWh × 1000 commonly called mills/kWh.

[3] Range due to near-term technology at twice cost goal and advanced system at cost goal.

[4] When required, annual capacity factor considered = 0.70.

[5] At power plant.

[6] Insolation is 2750 kWh/m^2yr direct beam at sunny wasteland.

[7] Oil at 30$/bbl international equivalent and includes distribution mark-up to end user, refining and combustion efficiency.

[8] Coal at 50$/ton and includes distribution, mark-up and inefficiencies if applicable.

[9] Nuclear at 1500$/kW(e) installed.

[10] Insolation is 1700 kWh/m^2yr direct beam which is 62% of sunny wasteland.

[11] 1.2 cost factor for small (100 kW(e)), modular, advanced systems.

[12] 1.4 cost factor for small nearer-term systems.

[13] Includes transmission and distribution at 90% efficiency and additional capital cost of 500$/kW at capacity factor = 0.50.

[14] Using thermo-chemical water splitting.

[15] Using electrolysis.

[16] Coal at 100$/ton.

[17] Coal at 150$/ton.

[18] Direct heating at nuclear plant.

[19] Resistance heat at load center.

[20] Global insolation at 2000 kWh/m^2yr.

[21] Global insolation at 1000 kWh/m yr.

[22] Only 40% of annual insolation considered available.

[23] Installed system cost at 225$/$m^2$.

Low temperature solar heat in good insolation (≈2000 kWh/m^2yr) on an all year round basis is competitive with oil or nuclear resistance heating.

Owing to the uncertainty of both solar and especially conventional energy sources, and the long time frame being considered, even these conclusions must be used with some caution. As suggested earlier, cost has not been the dominant driving force in past energy transitions, and may play an even smaller role in the future.

Photovoltaic Electricity

Photovoltaics, in which sunlight is directly converted to electricity, is the second most important solar R&D area in terms of financial support in the US and other countries. The single crystal silicon approach, which is the most developed as a result of aerospace activities, is currently the front-runner. It has made steady progress toward commercial terrestrial applications with a factor of 50 reduction in cost. However, the US program is still a factor of 20 from the 1986 cost goal of \$0.50/W_p for a module (peak watt based on maximum insolation of 1 kW/m^2). A photovoltaic module would be the dominating part of a system. The rest of the system is made up of the support structure, which is likely to be a fixed flat plate tilted at approximately the latitude angle if cost goals are reached, power conditioning (DC to AC), and power collection. Separate dedicated storage is possible but, more likely, the electric grid with its family of power plants and possibly central storage will be used with the photovoltaic system.

In addition to the silicon single-crystal program, gallium arsenide with its higher efficiencies (~20%), high concentration capability, and the insensitivity to higher temperatures (up to 200 °C), as well as amorphous silicon, thermophotovoltaic designs, vertical multijunction silicon, polycrystalline silicon, and cadmium sulfide-copper sulfide, are in the early development stage.

The distinctive features of photovoltaic systems are the lack of moving parts in the power generating module, the ability to use global insolation (direct and diffuse), and the possibility of using the waste heat (≈80% of incident) for low temperature heating needs. This type of system can be easily integrated into the built environment whether urban or rural, and retrofitting would be essentially as simple as inclusion in new construction. In addition to these on-site applications, neighborhood or central applications are possible. Silicon module efficiency of 12% to 18% is expected at the low cost goal, and efficiencies for all approaches are likely to be in the range of 6% to 30%.

There is broad confidence that \$1.00/W_p can be reached using mass production techniques with current technical approaches based on single-crystal silicon (Metz and Hammond, 1978). A recent study indicates that \$0.40/W_p is achievable

(Aster, 1978) using an optimized combination of known developments. However, further cost reductions may require the development of another approach. Since there are a large number of candidates in the early stage of development, some researchers are confident at least one approach will reach \$0.20/W_p to \$0.50/W_p. Because it is early in the R&D stage for these other approaches, this speculation has an unknown pedigree, and strong support can be found on both sides of this contention.

Estimates of photovoltaic plant performance and cost are shown in Figure 18 based on single-crystal silicon on a tilted flat plate structure costing 17.50\$/m^2 with a global radiation of 1900 kWh/m^2yr on this tilted plate. With this set of assumptions, some concentration (2:1) is attractive economically. A simple concentration scheme can be used with a fixed angle but asymmetrical "V" trough that is adjusted bi-annual (every six months) (Selcuk, 1977). This reduces the energy cost slightly (<10%) and reduces the overall area requirement by about 15% while roughly halving the photovoltaic area. A compound parabolic concentration (CPC) may be used with a three to five times concentration that is adjusted five to ten times a year. However, the cost estimates of Figure 18 simply use a flat plate scheme without concentration and are somewhat conservative.

At the cost goal of 0.50\$/W_p and without storage, the capital cost is about 1500\$/kW(e) at an annual capacity factor of 0.25. This assumes a global insolation level of 1900 kWh/m^2yr typical of sunny regions. The resulting electricity cost is 0.073\$/kWh as shown in Figure 12. Of the two main parameters, \$/W_p and module efficiency, it is \$/W_p that is the dominant cost drive. A factor of two reduction in \$/W_p (1.0 to 0.5) at constant efficiency will reduce energy cost by 40%. However, a factor of two increase in module efficiency (6.5% to 13%) will reduce energy cost only by 18%.

This particular design point at \$0.50/W_p and 13% module efficiency is shown in Figure 11 for comparison with solar thermal electric plants. To achieve a cost that is the average of the range shown for the solar thermal electric plants (~0.045\$/kWh), the module cost would have to be reduced to about \$0.22W_p, which is about half the 1986 goal. The ease of integration into roofs, accessibility of waste heat, use of global insolation (direct and diffuse), and simple maintenance all conspire to make photovoltaics more attractive than otherwise would be the case.

Orbital Satellite Solar Power (SPS)

The orbital satellite solar power system (SPS) is receiving intense study in the US to determine suitability as a commercial energy system. It is a solar power plant, part of which is located at 36,000 km above the earth in geosynchronous orbit (GSO) (i.e., the satellite maintains the same position over the earth). Electricity generation will most probably be with a

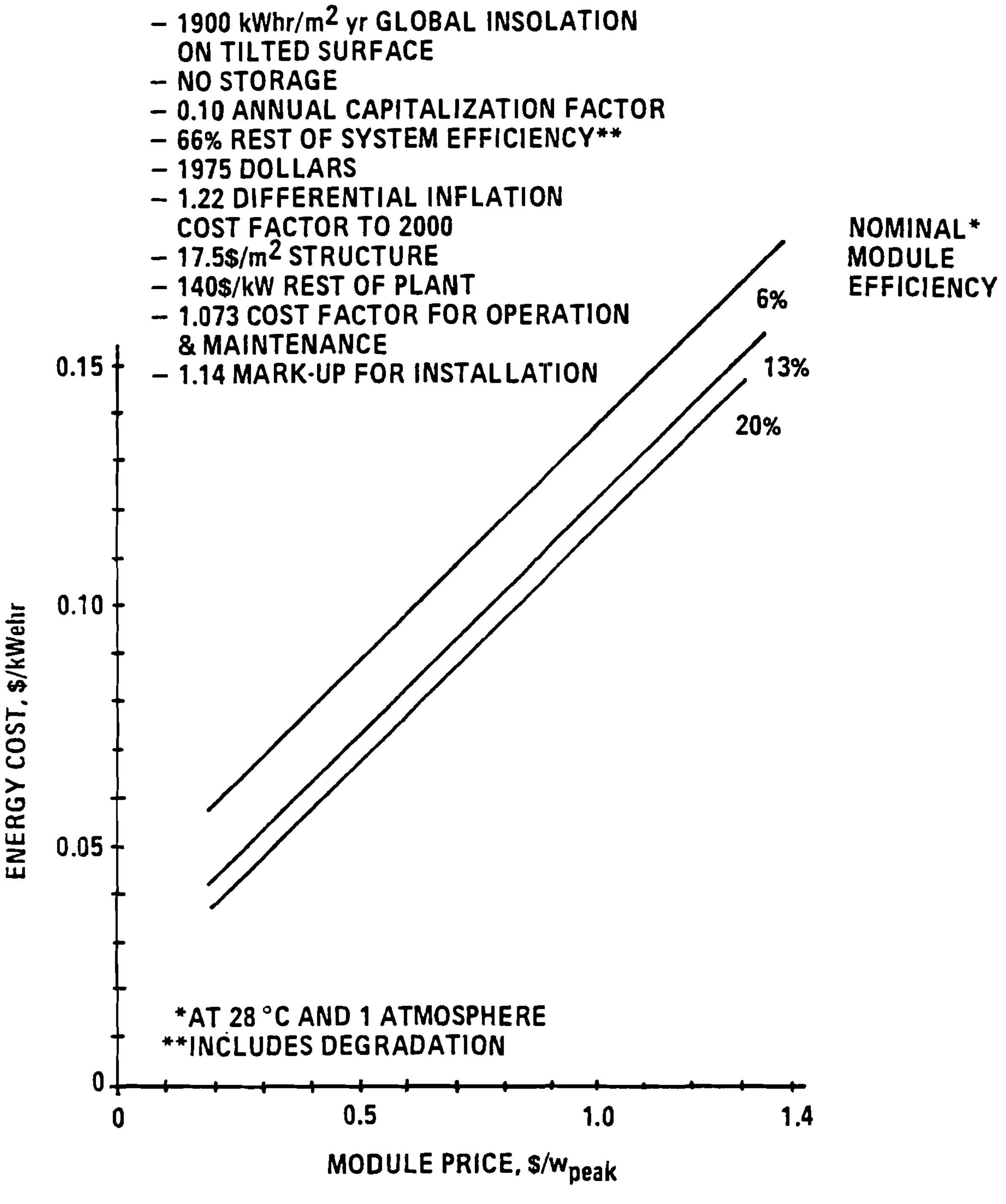


Figure 18. Photovoltaic electricity cost. See also Häfele (1981).

"space" version of the same photovoltaics that reach commercial development for terrestrial applications. The electricity will be converted to microwave energy and beamed down to a receiver-antenna (rectenna) on the earth.

The SPS is very large (~7 km × 15 km) and could weigh from 50 to 100 × 10^6 kg with about 30 to 50 km^2 of photovoltaic modules for 5000 MW(e) of electricity delivered to the ground via a coherent microwave beam. The microwave energy is converted back to DC electricity at the ground rectenna, collected at a central point, and then (converted) to AC for transmission to the load center.

The SPS power system includes not only the space power plant, the ground rectenna, and DC to AC conversion equipment, but includes the orbital support facilities, orbital construction facilities, transport systems from ground to geosynchronous orbit (GSO), ground launch facilities, and related ground support facilities. All materials are considered to be brought up from the earth although using mined materials from the moon has been suggested.

A post-shuttle transportation system must be developed for the SPS and may be a heavy lift launch vehicle (HLLV) with vertical take-off. However, horizontal take-off is also being considered. The launch vehicle would bring materials up to low earth orbit (LEO) at an altitude of approximately 400 miles. The form of most of the material would be bar stock and sheet metal rolls rather than finished subassemblies. A nearly automated factory would therefore have to be created to fabricate the satellite, probably in GSO. Transportation for one satellite would require 200-500 flights of the HLLV, which may be three to five times larger than today's Saturn 5 launch vehicle.

A 5 GW(e) rectenna on the earth would have a diameter of 11 km and an area of 75 km^2, with billions of individual half-wave dipole elements for microwave reception. The land area needed would be about 300 km^2 (20 km in diameter) to have a microwave radiation level of 0.10 mW/cm^2 at the rectenna boundary. (This radiation level is 1/100 of the current US standard for continuous exposure to microwave radiation.) However, if the Russian standard is used (0.01 mW/cm^2), the plant area would more than double to 770 km^2 per 5 GW(e) plant (31 km in diameter). For reference, the island of Manhattan in New York City has an area of less than 60 km^2, and lake Geneva is about 600 km^2.

The current estimate of the R&D cost to deliver the first SPS is about $90 billion (NASA, 1979). It should be pointed out that a similar description in 1960 of the requirements for the Apollo mission, which delivered man to the moon, would have seemed equally complicated and difficult. And even today a similar thing can be said of a description for a nuclear fusion electric power plant. However, there is a commitment today to support the R&D necessary to achieve the laboratory breakthrough necessary to verify the technical possibility of fusion. If and when that achievement is made, we will be faced with the next problem of determining the economic, environmental, and general social suitability of fusion power. In a sense, we have already reached the technical breakthrough stage for SPS in that there exists some laboratory or space flight hardware that provides almost all the required functions of the proposed SPS. We have experience with launch, recovery, low earth orbital and geosynchronous orbit satellites, altitude control, photovoltaics in space, microwave transmission, receiving and conversion to DC electricity, at least in the southwest North American deserts, human support systems, simple human assembly activities in space, and even some experience with ion propulsion. However, the scale and system compexity required are vastly different than current experience, and the requirement for economic competitiveness (or near economic competitiveness) in a commercial application is vastly different from historic space operations. Thus the SPS is at a stage equivalent to where fusion will be when it (fusion) achieves its technological breakthrough. Although this is stated repeatedly by SPS supporters, it may not be very significant since the decision to proceed with SPS development must be based on meeting economic and social requirements. The same will be true for fusion when its breakthrough is achieved.

Many questions have been raised specifically about the SPS in the areas of economics, utility interface complexity, environmental impacts due to launch pollutants and microwave transmission, human health impacts (both public and occupational) due to microwave, atmospheric pollutants and aborted launches, land use, siting difficutly, noise, microwave interference with communications, military vulnerability, diversion to weapon, R&D costs, technical risk, and social effects of its size.

The approach taken here is to use photovoltaics similar to the terrestrial photovoltoltaics developed to meet the 1986 US Department of Energy (DOE) goals ($0.50/W_p$) (Caputo, 1977). For all other subsystems of the SPS such as launch, orbital construction, microwave, etc., which are different from the terrestrial plant, "goals" used in 1976 in US studies will be utilized to define cost and performance. This exercise will *not* be useful in predicting absolute economics of the SPS since goals are used throughout, but it will address the question of what the SPS will cost compared with a ground plant with similar photovoltaics cost.

Thus the assumption is made that the estimated $90 billion investment (ECON, 1976) will achieve NASA (1979) "goals" and overcome the significant economic and technical uncertainties of the SPS, which are:

- photovoltaic performance and cost
- heavy lift launch vehicle and tug vehicle costs
- microwave link efficiency and cost
- economic feasibility of space construction in an orbital factory
- economic feasibility of constructing lightweight deployable structures.

Achievement of these objectives should be accomplished within whatever societal constraints exist that impact SPS design. Although NASA has had more success than most US government agencies in predicting the cost of completing new programs, it is difficult to know how valid this R&D to first SPS cost estimates really is.

These cost and performance estimates ("goals") used in 1976 were based on achieving a delivered energy cost of about 0.030\$/kW(e)h. Goals for each major subsystem were based on allocations that allowed this total energy cost to be achieved. These goals were never explicitly stated by NASA as such, but are taken from NASA contractors and field center studies in 1976 (ECON, 1976). This is the classic back-calculation to achieve the desired result, and is certainly useful in establishing about how far one has to go to achieve economic competitiveness.

For the terrestrial photovoltaic energy conversion system, the 1986 US DOE goal of \$0.50/W_p is used with an assumed module efficiency of 13% in air mass 1 (AM1) at a reference temperature of 28 °C. The cell efficiency without assembly into the module and electrical interconnections is greater than this module efficiency by 10% to 25%. Thus the assumed cell efficiency is about 15%. The terrestrial module is considered to be modified by further R&D to be more efficient and lighter at some extra production cost. Projections of design modification and resulting performance for the space photovoltaic module result in the following changes: cover thickness reduced from 30 to 60 mil for the terrestrial module to 1 to 3 mil for the space version; front and back surface enhancements improve performance by 25% but result in a module cost increase of about 60%; and the cell thickness is reduced to four mils (Caputo, 1977). However, when used in space at zero air mass (AM0) the module performance is reduced. Also considering an average performance degradation of 0.89 due to damage caused by normal and solar flare radiation, the improved and thinner module is estimated to be 12.5% efficient at 28 °C. When performance is corrected for the higher temperatures found in space at 2:1 concentration of insolation, the overall module efficiency is 8.4% averaged over the estimated 30 year SPS lifetime (Caputo, 1977). The resulting photovoltaic module cost is 104\$/m^2. The 0.89 factor for radiation-induced degradation averaged over the 30 year lifetime is considered to be optimistic and a lower value is probable.

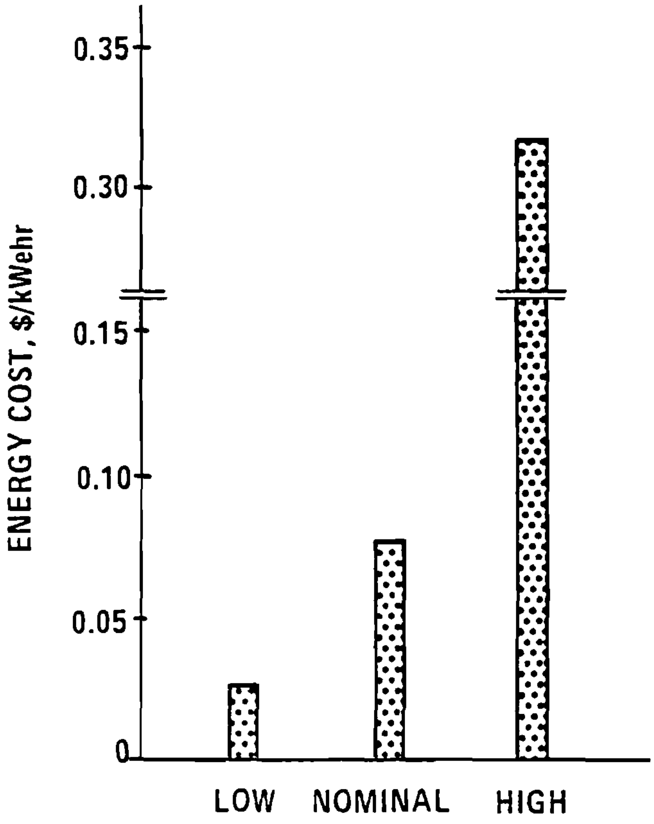
The total capital cost resulting from achieving these goals for a 2000 plant start-up in 1975 dollars is 5600\$/kW(e) or \$28 billion per 5 GW(e) SPS, including the 1.22 differential inflation factor used in previous solar electric calculations.

The resulting levelized energy cost is 0.077\$/kW(e)h, using a 0.10 annual capitalization factor. A sensitivity analysis of SPS parameters is performed where the "low" case is a combination of all the low cost and best performance parameters, while the "high" case is a combination of all the high cost and low performance parameters. These "low" to "high" cases should be considered near the extreme range of possibilities for the SPS. The resulting energy cost is in the range of 0.026 to 0.320$/kW(e)h as shown in Figure 19. The nominal energy cost (0.077$/kWh) is very close to the terrestrial photovoltaic energy cost (0.073$/kW(e)h) and is shown in Figure 5. Adjusting the terrestrial photovoltaic plant to an annual capcity factor of 0.70 (baseload) results in a capital cost of 5000$/kW(e) based on either pumped hydro storage or advanced batteries (Caputo, 1977). The energy cost at this design point is 0.088$/kW(e)h using a 0.10 annual capitalization factor. A similar sensitivity analysis to that shown in Figure 19 would produce a range from 0.047 to 0.140$/kW(e)h. Although large, this uncertainty is one-third of that for the SPS. This is due to the photovoltaic modules themselves being the major development area for the terrestrial plant, while a space version of a photovoltaic module needs both this development and development of the heavy lift launch vehicle, the microwave link, orbital construction techniques, and large, lightweight, deployable space structures for the SPS.

The land use of the SPS is from 2800 to 7200 m^2/MW(e)yr of contiguous land depending on the allowable microwave standard used to define the plant boundary (0.10 to 0.01 mW/cm^2). This is 300 to 770 km^2 per 5 GW(e) plant. The terrestrial photovoltaic plant, if it is not placed on roof area, would require 5400 m^2/MW(e)yr in good insolation based on a 30 year system life. Five GW(e) of base load terrestrial photovoltaic plant would cover about 580 km^2 if no roof area is used. Use of roof area would of course directly reduce land area impacts.

Thus both photovoltaic approaches seem to have similar energy and capital costs, but major differences exist in the program risk, magnitude of government R&D investment, uncertainty of eventual results, type of plant and interface with the electric grid. Significant differences also exist in the characteristics that give rise to social, political, military, and environmental impacts or considerations.

It is felt that possible "show stoppers" for the SPS are: the magnitude and risk of the R&D investment; plant siting due to the microwave beam health risk (real or perceived) and the need for very large contiguous land areas; microwave interference with communication; and atmospheric pollution due to launch activities and the microwave effect on the atmosphere. The potential microwave low level radiation health risk bears some similarity to the fission nuclear reactor radiation risk, and therefore one might expect similar kinds of difficulty in siting and public acceptance. There is also potential for weapon diversion due to either the microwave beam or the availability of this large power supply in space. This last potential may produce the impetus for the large R&D investment, but also could require an international team to be involved in development.



	LOW	NOMINAL	HIGH
PAYLOAD COST TO 650, $\$/\text{kg}$	71	145	209
SOLAR BLANKET COST, $\$/\text{m}^2$	48	104	160
SOLAR BLANKET EFF., %	9.7	8.4	6.2
CELL THICKNESS, MILS	2	4	10
ARRAY STRUCTURAL WT., kg/m^2	0.092	0.18	0.37
MICROWAVE SYSTEM EFF., %	70	60	40
MICROWAVE SYSTEM COST, $\$/\text{kW}$	332	520	840
MICROWAVE SPACE BORN WT., kg/kW	1.16	1.33	1.54
D & M COST, $10^6\ \$/\text{yr}$	33	108	150
CONSTRUCTION TIME, yrs	3	6	10
CAPACITY FACTOR	0.99	0.86	0.75

Figure 19. Photovoltaic SPS cost sensitivity.

Possible Resources and Materials Constraints

Of the activities associated with a solar plant it is the construction of the plant and the acquisition of construction materials that would most likely have the greatest societal impacts, although the operation and decommissioning of solar facilities used at the multi-terawatt level may also result in substantial environmental impacts. "Because more concrete and steel are required for a combination of solar technologies than for, say, the fast breeder fuel cycle, the environmental consequences of additional iron ore extraction, steel making, concrete production, etc., must be charged against the decision to "go solar" rather than nuclear" (Weingart, 1979). In addition to the magnitude of environmental consequences, we must keep in mind the associated distributional questions. For example, "steel making and the like are highly local activities, where the burden of pollution is felt directly. The air in Gary, Indiana, may be fouler because STEC plants keep the air clear in New Mexico" by reducing coal production (Weingart, 1979). Solar generated fuels may warm houses in northern F.R.G. at the expense of widespread disruption, due to central solar plants, of the ecosystem in central Spain.

Some feeling for the materials requirements for construction and maintenance of a solar energy system can be obtained from Table 6 (Caputo, 1977). Most solar energy systems are material intensive, in order to convert the low intensity incident radiation to other forms of more concentrated energy. Because these systems must operate in a variety of natural environments, they must also have sufficient structural stability to insure operation and survival under occasional extreme conditions as well as continuous "routine" environmental conditions. This requirement translates into a mass density per unit area. The minimum density of a system that can withstand the weather for decades is likely to be at least 10 kg/m^2. This might be a tough, thin film photovoltaic system interconnected and supported by lightweight space frame techniques. If placed on a roof with minimum framing, the material density would be closer to 5 kg/m^2.

The initial US prototype (McDonnel Douglas, Martin Marietta and Honeywell) heliostats for STEC plants weigh about 65 kg/m^2 considering the steel and glass but excluding concrete. The concrete and sand are considered to add about 134 kg/m^2 to the heliostat weight. The rest of the plant adds about 154 kg/m^2 of concrete including 12.6 kg/m^2 of steel. The next generation heliostat designs (Selvage, 1980) were about 50 kg/m^2. The current designs are closer to 35 kg/m^2. However, the steel and glass in some European prototype designs (Soterem and Cethel) are about 80 kg/m^2 (Saumon, 1977). Some unique heliostat designs (Boeing) have achieved 30 kg/m^2 for steel and glass even at the prototype stage, but with just as high a concrete requirement. A more recent design by General Electric keeps the low steel and glass a requirement (~30 kg/m^2), but substantially substitutes rock for the concrete. Although the mass is similar, rock has a reduced environmental impact per ton of production than does conconrete.

Table 6. Material requirements per annual TWyr/yr. Adapted from Häfele (1981).

	Mirror Area[1] $\frac{10^6 km^2}{TWyr/yr}$	Mirror Density kg/m^2	Material Required[2] $\frac{10^6 ton/yr}{TWyr/yr}$
Central solar thermal[3]			
Steel and glass material			
- Electrolysis	0.0129	48[4]	620
- Thermochemical	0.0048	42[5]	200
Total material			
- Electrolysis	0.0129	325[6]	4200
- Thermochemical	0.0048	325[6]	1560
Photovoltaic			
Central[7]	0.035	10	350
Roof top[8]	0.0538	5	270
Flat plate collector			
Winter heating[9,11]	0.0245	50[12]	1220
Hot Water[10,11]	0.0092	50[12]	460

[1] Mirror area per TWyr/yr primary equivalent based on 25% end-use electricity, 25% transportation liquids and 50% heat.

[2] Material per TWyr/yr energy produced per year in metric tons.

[3] 2750 kWh/m^2yr direct beam insolation

[4] 3rd generation US prototype heliostats using glass including steel in tower/receiver.

[5] Novel design using stretched aluminized mylar in a plastic dome.

[6] Central receiver plant includes concrete (86%), steel (12%), glass (2%).

[7] 2000 kWh/m^2yr global insolation.

[8] 1200 kWh/m^2yr global insolation.

[9] Annual solar efficiency = 15%.

[10] Annual solar efficiency = 40%.

[11] 1500 kWh/m^2yr global insolation.

[12] Approximate for metal glass collectors.

Figure 20 shows these data as a function of, first annual and, second total energy production after 100 years. Even at 35 TWyr/yr (which is 0.35 TWyr/yr per year for 100 years), it requires about 550 × 10^6 ton/yr for the solar thermo-chemical hydrogen system (~70 × 10^6 ton/yr of steel, ~10 × 10^6 ton/yr of glass and the rest concrete). As a rough measure of what this represents, present (1975) annual global production of concrete is 700 × 10^6 ton/yr, steel is 630 × 10^6 ton/yr, and glass is 1070 × 10^6 ton/yr (UN, 1975). The current global production of concrete is about two thirds of what would be required to produce 0.35 TWyr/yr energy each year; steel production is now 10 times more than what would be required, while glass is 100

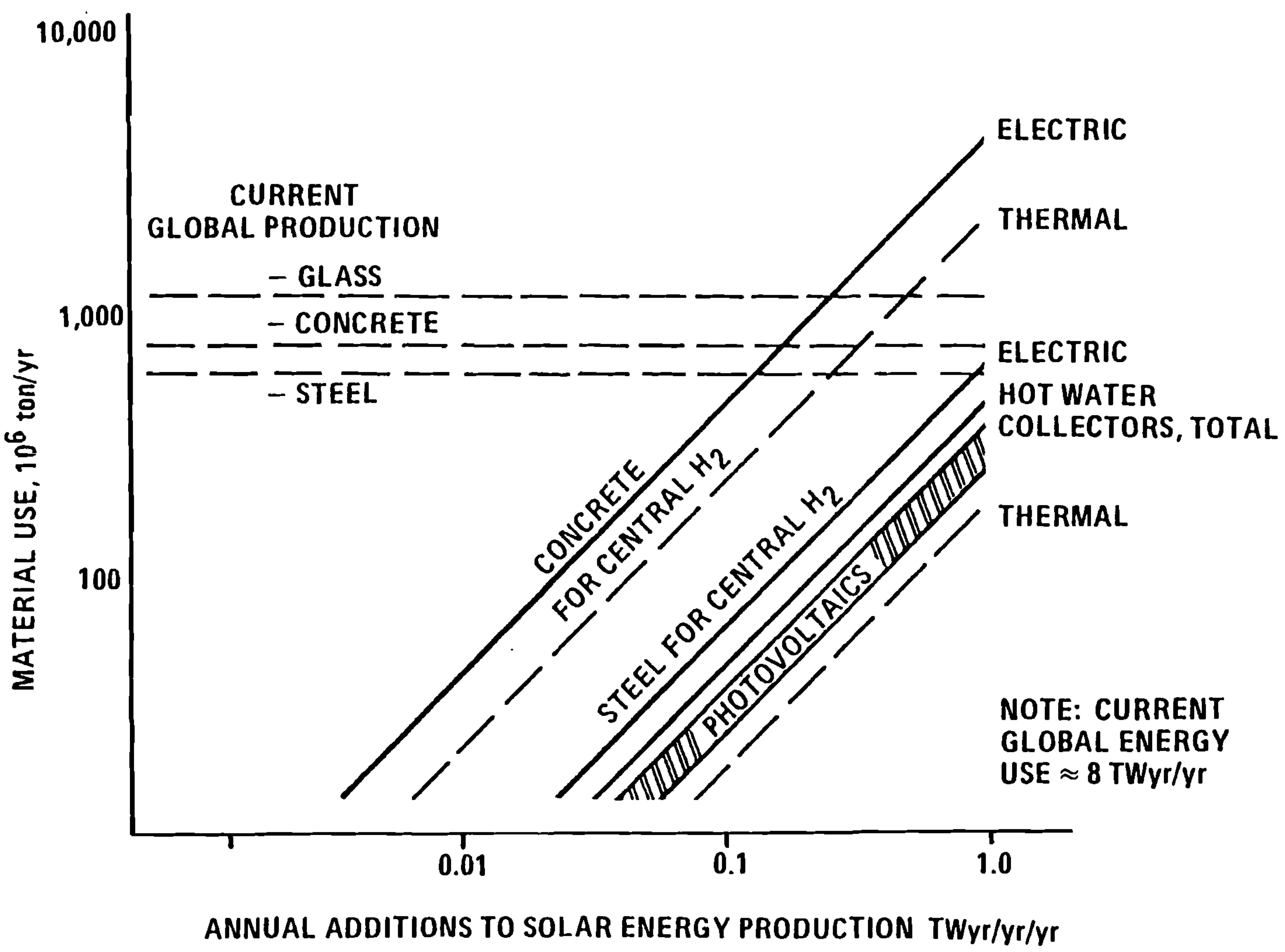


Figure 20. Material requirements for central solar systems. Adapted from Häfele (1981). Note: Electric stands for electrolytic hydrogen, and thermal for thermochemical hydrogen.

times more. The photovoltaics are more attractive especially if roof top (or south-facing wall) systems are used. However, the material requirements presented here should more properly be compared with the global material use projected in the future. In the 35 TWyr/yr scenario described earlier in this paper, the steel production in 2030 is projected to be 4 times today's volume, while concrete production will be 5.5 times today's value. The projected use of concrete for solar construction is therefore about 12% of 2030 production.

Thus only concrete requirements would exceed 5% of projected production by 2030 for the assumed case and that would occur only if central solar electric systems are considered to provide all 0.35 TWyr/yr of new energy production each year. This is a conservative estimate in that this type of central solar system is concrete intensive. If distributed collectors without central towers are used instead of central receiver solar systems, then half the concrete and about 10% of the steel is not required.

To the extent that roof collectors, biomass systems, SPS, ocean and thermal systems are used, the concrete requirements would be reduced. Thermochemical hydrogen would decrease the material requirements by over a factor of 2, and extensive use of efficient photovoltaics would reduce material use even more significantly. Taking these possibilities into account, it is estimated that the solar concrete requirement would be less than 5% of projected production. Finally, it should be noted that the ingredients of concrete are some of the more common materials on the planet, and the length of time available (≈50 years) to build up this slightly increased production capacity is reasonable.

The relative amount of non-fuel construction material required for solar thermal electricity is obviously many times that required for a coal or nuclear power plant. For steel, the ratio of material for a solar compared with a coal energy system is about 12:1 while it is about 17:1 for a nuclear energy system (light water reactor). For concrete, a solar plant requires about 60 times that needed for a coal and about 14 times that of a nuclear energy system. The basis for comparison is per unit electric energy generated over the plant lifetime of 30 years (Caputo, 1977).

If the fuel for a coal plant is included in its use of materials, it dwarfs the use of construction material even when compared with a solar thermal electric plant. The coal use is 3 million kg/MW(e)yr compared with about 0.2 to 0.3 million kg/MW(e)yr of total material for the solar plant.

The construction and maintenance of a solar system of the global scale would thus require large amounts of materials. In order for sunlight to be translated into a globally interesting energy option, we should develop systems that are inherently low in mass with long lifetime or allow a high use of recycling materials. This suggests that technological breakthroughs that permit low mass, high environmental resistance and long lifetime are desirable.

We should note that these observations on material requirements for the installation of solar power in the TW-range are fully consistent with the notion of consumptive and investive uses of resources as developed in Häfele (1981). Indeed, solar "fuel" is free but it requires large-scale investments of materials, i.e., resources, to have that solar "fuel" collected and transformed into a viable secondary energy carrier, be it electricity or hydrogen. These investments of resources continually pay off by providing such secondary energy. What has to be balanced then is the size of the investment, the rate of depreciation and the rate of providing secondary energy; and the investive use of resources has to be compared with consumptive uses such as a level of mining fossil resources, which would be comparable to the yearly depreciation associated with the investive uses of resources. In fact, Figure 20 was conceived and should be read with such a comparison in mind.

Such extensive materials processing is not without some impact on the environment. However, studies have shown that even for a bullish solar economy in the US, the additional effluents will be on the average negligible when compared with the total impact of all activities in the economy (Davidson and Grether, 1977). Also, the energy system life-cycle health effects of a central solar electric baseload power plant have been estimated (Caputo, 1977) to be two orders of magnitude lower than those for "clean" coal electricity, that is coal mining with US 1969 dust standards enforced and $99^{+}\%$ of sulfur removal prior to combustion. This estimate includes fuel acquisition and operation as well as the indirect activities involved in plant construction and acquiring construction materials.

Possible Environmental Constraints Associated with Climate Impacts

"The potential consequences of global deployment of solar energy are of special concern. From experience in the field of fission power, we know that in the beginning of the technological development period, the large-scale aspects of the technology are often not thoroughly examined (or even perceived). Only when large-scale activity commences do such considerations become visible and important. From hindsight we realize that the development of a strong, systems-oriented technology assessment of the fission option, including social valuing integrated with the political process probably would have made a substantial contribution to the recognition and resolution of problems that are now inhibiting the use of such technologies."

"Solar energy conversion systems are relatively benign but will be no exception to the rule that the large-scale use of any new technology bears unexpected and often undesired consequences. Although there appears to be a great deal of popular support for the idea that the use of sunlight is completely "clean", this contention will fall if large areas of desert lands are covered with machines, valleys are flodded to provide hydroelectric facilities, and scenic coast lines are dotted with thousands of towers holding wind generators. The possibilities of climatic modification appear when we consider covering upwards of a million square kilometers of sunny land with solar conversion machines" (Weingart 1977a and 1977b in Williams et al., 1977).

An anomaly in one part of the total climate system, which is highly complex and non-linear, may be expected to trigger a series of changes in other variables, depending on the type, location and magnitude of the initial anomaly. When considering the impact of large-scale deployment of solar-thermal electricity generation on climate, we are concerned with anomalies introduced in the interaction between the land surface and the atmosphere. The physical characteristics of heliostat arrays can influence several climatic boundary conditions, in particular the albedo, surface roughness and hydrological characteristics of the land surface (Berkofsky, 1976). However, since there is no direct observational evidence of such anomalies, discussion must be based on observations of analogous situations in the climate system or upon the results of numerical models of climate. A preliminary assessment of the implications of the sorts of changes in physical characteristics listed above has been made (Williams et al., 1976).

Studies of the effects of large-scale albedo changes have shown that on the local scale,a decrease (increase) of surface albedo in a desert region could lead to increased (decreased) vertical velocity of the air and thus possibly to increased (decreased) rainfall (Moore, 1976). Further studies have indicated that such effects can also be expected on a larger scale and that when the anomaly is large enough, feedbacks within the climate system cause related changes to occur in areas other than where the initial perturbation is introduced (Williams et al., 1976). It has been calculated that the least dimension of the area for which albedo and surface moisture changes can be expected to influence convective rainfall is a length of 40 - 80 km (Williams et al., 1976). If a circular area is devoted to 1 TWyr/yr solar capacity, it would have a diameter of approximately 200 km.

The other two boundary conditions (surface roughness and hydrological characteristics) affected by solar-thermal electric conversion have not been considered so extensively in model experiments as has albedo.

In addition to changing the local albedo, surface roughness and hydrological characteristics, a solar plant may have a more direct impact on the local heat balance. However, rather than just calculating the waste heat from a plant, it is more appropriate to identify the excess waste heat. The excess waste heat is that heat released at the plant that is in excess of what would have been released if the plant were not there. For coal and nuclear, all the heat rejected at the plant is excess waste heat, as is also the case for the SPS at the ground rectenna and in the atmosphere due to the microwave beam losses. However, ground solar thermal and photovoltaic plants are using solar energy that normally would strike the ground and heat the area to a certain extent. Some of the sunlight is "bounced" (reflected) off the ground and sent back up into the sky (albedo), while the remainder is absorbed by the ground. Part of this absorbed energy heats the ground and surrounding air, while the rest radiates to the surrounding environment at a longer wavelength than sunlight. Under certain conditions, it is possible for a ground solar plant to produce no excess waste heat. See for example Caputo (1977) where it was concluded that there is almost no net difference in a land area's heat balance before and after a solar thermal electric plant is located there. The amount of excess waste heat rejected per unit electrical energy generated for various power plants is shown below in Table 7. The soil albedo is assumed to be 0.30. The solar thermal plant has about an order of magnitude less excess waste heat compared with conventional plants, while the ground photovoltaic is similar to conventional plants if sited in a desert. However, roof top application would have almost no excess waste heat since common roof materials have albedo similar to photovoltaic materials.

Also assuming that the natural albedo of the desert land is 30%, an evaluation by C.M. Bhumralkar of Stanford Research Institute and Jäger, Chebotarev and Williams (1978) at IIASA suggest that the albedo of the area is reduced when a STEC plant is present. However, the total energy emitted from the earth's surface to the lower atmosphere in the form of long-wave radiation, sensible and latent heating remains about the same when the STEC plant is introduced, implying that *there would be no net heating or cooling of the lower atmosphere*. The major difference when the STEC plant is present is that the long-wave radiation from the surface is reduced by 10-25% while the amount of sensive and latent heat is increased in accordance. Much of the latter increase is accounted for by the waste heat release during electricity generation. If dry cooling towers or radiators are used, or if open cycle air gas turbines are used, the waste heat will not have moisture. This avoids any imbalances due to moist plumes which would cause most of the anticipated climatic impacts.

Thus for an average power generation on the order of 50 GW(e), the climatic impact of wet cooling towers would be noticeable in a desert climate, but perhaps not in a moist climate; once-through cooling systems would have a noticeable effect on regional scales; and dry cooling systems seem always to have a negligible impact on regional climate averages (Sawyer, 1965). While the local changes in climate caused by changes in energy balance and waste heat release are most likely to be manifested in cloudiness and precipitation changes if wet cooling is used, the large-scale deployment of STEC could cause an anomaly large enough to trigger changes elsewhere. A discussion of the causes of long-term weather anomalies shows that large-scale weather or climate phenomena are produced by differential heating when this occurs on a "synoptic" scale, i.e., over closed areas with a magnitude of 10^5-10^6 km^2, and when the heating varies locally by 20 W/m or more (Jäger, 1978). The deployment

Table 7. Excess waste heat for several types of electric power plants (assumed soil albedo 0.3).

Type of plant	MW(th)yr/MW(e)yr
Coal (gasification)	1.7
Nuclear (LWR)	2.1
Solar	
Thermal	0.25
Ground photovoltaic	1.5*
Orbital photovoltaic	0.25

*would reduce significantly if rooftop application rather than desert sites.

of STEC over an area of several thousand square kilometers could certainly be constrained by climate considerations only if wet cooling towers are used. Due to water restrictions alone, dry cooling is likely by the year 2000 (Caputo, 1977).

For solar plants in arid regions the solar thermal plant performance and cost estimates used previously were based on dry cooling specifically to minimize potential climatic impacts and minimize water consumption.

Possible Constraints Due to Social Preference

While the analysis of social preferences is beyond the scope of this paper, it is important that we consider constraints on solar development that might be introduced by changing public opinion. Earlier in this chapter we observed that the possible replacement of gas by nuclear as the dominant energy form could be moderated or even prevented from happening due to a newly developing social consciousness. This social tolerance of energy systems may be such that a combination of renewable and central solar is acceptable while nuclear is not. Yet there is increasing evidence that it is also the large central monolithic aspect of energy systems that is coming under increasing social criticism (Gerlach and Radcliffe, 1979).

This resistance to large projects seems to come from a keener sense that some people pay most of the price for intensified energy system development that primarily benefits others. People who have been relatively disfranchised have learned how to become more effective at having their concerns responded to by usually more powerful economic and political interests. This more effective behavior usually involves almost leaderless, multi-group cooperation in trying to block large development by central authorities. The groups collaborating come from a very wide social spectrum and appear to have little in common except the cause of interrupting this unwanted development.

It is almost as if the increasing attention being given globally to the "first" and "third" world countries and the historically unbalanced economic relationship they have had, is extending down to more or less powerful groups even within a developed country. What we may be witnessing is a basic social phenomenon that extends from national governments down to small citizen groups. The common intent seems to be a balancing of diverse interests that were ignored by earlier ways of doing things.

If this indeed turns out to be the case, large central anything energy systems would be rejected by society whether nuclear, solar or whatever. If not rejected, then severe conditions put on their use would limit their availability. In this case, renewable energy both direct and indirect that is user-oriented may be the only major energy option allowed for the future.

It may prove to be the cultural adaptability of renewable energy systems that is the single most important aspect of this family of energy systems. Cultural adaptability is the capacity of solar technologies to be configured over a wide spectrum of social arrangements. For most renewable energy forms, both individual ownership as well as large corporate ownership is possible. Large central monolithic as well as modular individual consumer systems are possible. Both mass production techniques typical of industrialized society are usable as well as cottage industry, "backyard" innovator techniques. This versatility in size, ownership, and construction techniques offers the greatest hedge against the uncertainties of the future. No other energy source has this cultural "switch hitting" ability.

We recognize that the development of a major solar energy system with little or no large central solar plants would require much more care and attention to system streamlining aspects than would be necessary if central solar were included. But questions of the adequacy of the resource magnitude when configured in this way or that way are not really relevant since if society demands a certain type of configuration, it will certainly adapt its consumptive patterns to use the thing it is demanding. Arguments that assume a certain type of future society with intense energy and other consumptive patterns, and use this to prove that certain types of renewable energy can not possibly be used, are indeed null arguments.

SOME POLITICAL ISSUES

As discussed in the section on the magnitude of the central solar resource, many of the globally favorable solar areas exist in what are poorer parts of the world. To the extent that these areas are eventually used for central solar production, they contribute to a resolution of the "North-South" problem which has economic imbalance at its roots. At the global level, solar systems are a southerly resource that can be developed with technology and capital from the North to create an interdependent economic relationship. Although this is similar in some respects to the history and current situation globally with oil transfers among nations, there appears to be a number of differences that bear examining. The likely energy carrier of this global level solar energy system is gaseous hydrogen. Other possibilities exist and may be used in special situations such as electricity, liquid hydrogen at cryogenic temperatures, ammonia (NH_3), or methanol (CH_3OH). However the land based solar rich areas are near large natural gas fields. This gas resource may eventually be utilized as part of the next dominant global energy system. To facilitate the use of this resource, gas pipelines will be installed to more easily bring this energy form to major load centers on almost all continents.

For example, this has already been done in the US which has the oldest major fields in existing pipeline system from the East Texas fields to both the central/north eastern part of the country and to the south west. The hub of the origin of this pipeline network is on the edge of the solar rich eight state sun belt estimated to be 0.05 to 0.40 million km^2. This area could generate from 1.8 to 16 TWyr/yr primary equivalent energy with 67% confidence. The average of this range is about 6 times greater than current US use of primary energy. In addition to the historic gas network, new links are being considered from Alaska and Canada, as well as from the developing Mexican fields. This continental level networking of gas carrying lines could facilitate the use of the Mexican and US solar resource eventually with hydrogen as an energy carrier from Alaska to Central America.

A similar situation exists (although currently less developed) in almost all the major solar areas. The North African and Middle Eastern gas fields are now being connected via pipelines under construction through Sicily and also through Crimean Russia. Both of these will take advantage of the existing natural gas network in Italy as well as in south west Russia for connection to Central and Eastern Europe. Additional links are planned through Spain and contemplated across Turkey. This vast gas pipeline infrastructure could be available to the solar generated hydrogen eventually. We are all familiar with the similarities to oil dependence, but how is it different?

Solar energy is not a resource that already exists in convenient underground storage media that can actually increase in value if not used today. Solar is obviously a resource that is available on a daily basis and if not used it is lost. One would have to store the energy. This could be done in the nearby formations which would be depleted of fossil resources. However the capital intensive investment made to create the solar plants would have no return until this storage energy was finally sold. This is different from oil today in that it is about 2 orders of magnitude less capital intensive than the projected solar systems. There is a very small up-front investment in oil and it is already stored conveniently.

Another major difference with oil is the pipeline link itself. Diverting pipeline energy is possible but vastly different than diverting oil tankers. To divert pipeline gas to a non-pipeline user of energy would require installing facilities to convert the gas into a more mobile energy carrier such as liquid hydrogen. These facilities would be large, and take a number of years if not decades to build along with the required cryogenic tankers and receiver port facilities. This extended period of time would give the pipeline energy user adequate time to further diversify his energy sources.

In addition, the conversion to liquid from gas can at best be achieved at 70% conversion efficiency. Thus the economics of liquid hydrogen is nearly 50% more expensive than pipeline hydrogen uses. For example, this difference is about the difference in cost of generating solar hydrogen in southern Europe compared to northern Africa. Thus in this case, the Europeans can further develop southern European resources at about the same cost of liquid hydrogen from good global solar areas.

Thus the whole relationship between solar supplier and pipeline user is much more balanced than the current oil situation. It is more of a marriage than a fleeting affair. This should lend political and economic stability to the relationship and be the basis of a more satisfactory North-South interdependence.

SOME PLAUSIBLE OIL/NATURAL GAS/SOLAR ENERGY PROJECTIONS

At the beginning of this paper we sketched an energy system projection in which gas succeeded oil as the dominant energy source, and was in turn overtaken by nuclear globally by about 2060. Much of the eventual nuclear capacity was assumed to produce hydrogen, which could then be distributed using the infrastructure that had been developed for natural gas distribution. The rest of the nuclear capacity would produce electricity and methanol. What has subsequently emerged from our examination of possible constraints to solar development is an energy trajectory in which solar either supplements nuclear or eventually displaces it as the principal energy source. Just as in the case of nuclear, solar could be used to produce hydrogen, electricity, methanol, as well as heat directly. The third possibility is that nuclear drops out prematurely due to social unacceptability and solar follows natural gas as a global energy source.

Having examined up to this point the characteristics of the different subsystems that might contribute to such a major solar energy system, it is instructive to step back for a moment and look at solar from a more aggregate perspective.

The penetration rates of solar energy options will depend on macrosystem characteristics as well as the competitive situations of all energy sources including economic and social factors. Uncertain cost estimates for most potentially significant solar options and uncertainty about the importance and nature of social factors limit the procedures that can be used to determine the solar market penetration rates. In addition, there are strong reasons to believe that the present costs will come down in the future, in some cases (e.g., photovoltaics) dramatically and fairly rapidly.

Initially, during the developmental phases, external capital is used to support new technologies even if their direct costs are somewhat higher than the competition. However, after these achieve a market share of a few percent and achieve commercial maturity their penetration rates may depend on their overall competitive situation: completely non-profitable technologies are rarely supported for very long time periods. This will also be the case, we expect, with solar options once they achieve significant shares of the primary energy market.

In the past it has always required roughly one century for the various traditional primary energy forms to go from a 1% share to a 50% share of the world primary energy market, though in particular countries the time period to go from a 1% to 50% market share has been more on the order of 25 to 100 years. An understanding of the time required for new energy systems to make major contributions to energy supply is crucial to any realistic assessment of the potential role of solar and nuclear energy, whether in a single country or worldwide. Yet the present projections for future US energy demand and the possible contributions from solar energy display enormous dispersion ranging from a few percent to 50% by 2030.

Let us therefore return once again to the trends suggested by Figure 1 and this time attempt some qualitative extrapolations in which "new solar" plays a more substantial role than it did in our original oil/natural gas/nuclear energy trajectory. The phrase "new solar" is used to distinguish between new or expanded uses, and historic uses of solar energy such as hydroelectric, wood burned directly in homes, forest and agricultural industry wastes used for process heat and electricity, burning of animal wastes for cooking and animal mechanical power. In the US, these amount to about 5% or 6% of current primary use, while in India they currently contribute about 60% (Fuel Policy Committee, 1974). Other than hydroelectric, these solar contributions are not usually considered in energy supply statistics since they are not sold commercially.

New solar is used to describe new industries formed using new processes in applying solar technology in new ways. The exponential growth should be applied only to these new processes. The old uses of solar should be treated in a different manner depending on the historic trends associated with each activity. For now it can be considered as a constant market share on a global level. Even though the percentage of use of some of these old solar applications may change dramatically for some developing countries, the low magnitude of this energy source will support the assumption of constant global share. This "old solar" should simply be added to the exponentially growing new solar areas. Assuming the traditional time constant of 100 years for new solar and assuming 1% new solar global penetration by 2000, solar technologies would provide half of the global energy by 2100 as shown in Figure 21.

If nuclear is not used and solar is introduced at 1% global by 2000, then gas use would probably be more extensive to "cover" this late introduction of solar. If one optimistically assumes a 4% new global penetration by 2000, possibly because of a lack of nuclear utilization due to its social unacceptability, then it would only take to 2060 to reach half the global energy and 80% would be achieved by 2100. This penetration trajectory can be seen by referring back to Figure 2 and considering the dotted line to be new solar.

These speculations show a range of possible introduction for solar energy based on historic trends as described in Marchetti and Nakicenovic (1979). Depending on the assumption of 1% solar by 1970 to 2000 and the significance of nuclear globally, 10% global usage would be achieved by 2020 to 2050, and 50% use by 2070 to 2100. The 100-year period to go from 1% tc 50% global use is typical of the previous primary energy forms, and while introduction rates different from these may be possible they are clearly beyond the scope of this inquiry.

Solar is a family of technologies, each at a different stage in the development process. Moreover, as a group the solar technologies have some special characteristics, which distinguish them from more familiar energy sources. For example, current energy sources such as oil can be used for multiple end uses such as being refined for auto transport, uses in residential heating, or industrial process heat, the gathering, transport, storage. Although a different grade of oil may be used for these applications, the oil is more similar than different. This is not so for the solar family. There are differences at each stage of development for most of the solar approaches. Some solar approaches involve a limited number of decision makers (i.e., central electric for utilities), while others involve literally millions of decision makers (i.e., residential hot-water heating, or use of residential wood burners for heating). Some approaches depend on industrial mass production by very large manufacturers, while others depend on more individualized crafts such as the building industry (i.e., passive homes) or user labor as in "backyard" solar collectors or biogas generators.

Thus the initial commercial entry time for each solar technology will be different and the adoption and diffusion process will be different. To characterize new solar penetration rates as a single composite that behaves as historic energy sources have, is certainly a gross simplification. Some types of solar may indeed follow historic trends, while others will not. How they all come together is difficult to predict. Thus the simplified approach used here is justified to a great extent due to the great complexity of the actual situation.

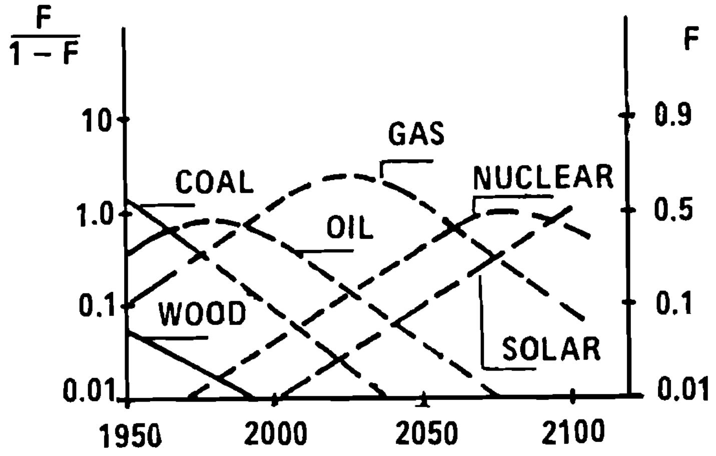


Figure 21. Solar energy introduction after nuclear in business-as-usual projection of world primary energy mix. Adapted from Marchetti and Nakicenovic (1979) with SOLAR originally identified as SOLFUS, i.e. solar and fusion.

CONCLUSIONS

What can we conclude from all this?

First, it is clear that a menu of solar energy systems technologies must take their place alongside the breeder as a possible long-term energy source for mankind. Fusion eventually could take its place as a third possibility. Any of these options is capable of providing all the energy we could conceivably need for as long as we are likely to inhabit our planet. It is estimated that 80 to 280 TWyr/yr are possible based on a combination of solar systems from on-site to global level systems.

Second, it is the combination of the large-scale use of solar energy in central ("hard") technologies for the production of electricity and synthetic gaseous and liquid fuels, along with the indirect and on-site ("soft") technology option that make this significant contribution possible. Individual small-scale solar energy units can be embedded in a harmonious way in large solar electric and fuel networks, with the fuel network providing the chief solution to the macrosystem streamlining requirement, i.e., storage. The backup to these solar systems will come from existing conventional fuels initially, and eventually from central solar hydrogen, methanol, biomass in the form of gases, liquids and solids, seasonal heat storage, and hydroelectric to some extent.

Thus solar systems taken as an interwoven family, have favorable macrosystem characteristics in that they are "streamlined" enough and renewable to be considered seriously as the eventual replacement for gas or nuclear energy.

Third, a global solar option would exhibit enormous heterogeneity, reflecting the great variations in geophysical resources, climate and social structure. Furthermore, its ability to function well with various social arrangements ("cultural switch hitting") may be its most significant characteristic.

Fourth, solar energy systems are already economically competitive in several important end uses. For example, current solar high temperature industrial process heat systems and solar hot water systems installed at $225\$/\text{m}^2$ are competitive (without subsidies) with international oil and baseload electricity in good clear sky locations (insolation ≥ 2000 kWh/m^{2}yr). Passive designs are cost effective in areas where local builders are familiar with this type of design and construction practice. Expected increases in conventional energy prices and solar cost improvements will improve solar competitiveness. For example, when solar thermochemical hydrogen systems are delivered at heliostat cost goals ($70\$/\text{m}^2$) delivered heat will be economically competitive with $15\$$/bbl international oil in 1975 dollars. Also central solar electric at cost goals will be economically competitive with $1700\$$/kW(e) baseload nuclear.

Fifth, substantial and global solar use after the gas cycle depends strongly on the social unacceptability of nuclear power as a global energy system.

Sixth, although the environmental consequences of such large-scale use of sunlight will not be entirely benign (since, for example, they include the health effects of material intensive industries), they appear highly manageable and orders of magnitude lower than conventional fossil systems, and with the exception of the SPS (orbital station), do not have any of the radiation hazards and risk aspects of nuclear power.

Seventh, plant construction material requirements are much greater than conventional systems, and some care must be taken to develop a materially efficient system. Concrete use may be significant ($\simeq 5\%$ projected global production) but it is a commonly available material.

Eighth, the emergence of a global solar energy system could perhaps bring with it an unprecedented North-South international interdependence and cooperation, and a substantial potential for development and growth in many poor but sun-rich regions. This would contribute to an easing of the economic and political imbalances that currently exist between "North" and "South".

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