EVALUATING THE SOLAR ENERGY OPTION AS A LONG-TERM MAJOR ENERGY OPTION FOR MANKIND

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Evaluating the Solar Option

Solar energy is one of the four energy sources adequate in theory to power human societies for the long-term (along with geothermal energy, uranium and thorium in the breeder reactor, and lithium and deuterium via fusion reactors). Although inexhaustible in human historical terms,,of high thermodynamic quality, and not subject to foreign embargo, sunlight has characteristics which make it difficult to harvest economically on large scales. It is of low power density (in the order of 1 kw/m^2 peak power) at the earth's surface and is subject to the diurnal cycle, seasonal variations and the multiple effects of weather and climate. Nevertheless, the convergence of a number of recent trends in energy prices and availability, environmental concerns and technological advances indicate that the conversion of sunlight into heat (for water heating, space conditioning

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and certain industrial processes) shaft horsepower, electricity and synthetic fuels (such as hydrogen) may, in many parts of the world over the coming hundred years, prove to be economically attractive on a very large scale.

In the long-term, it is likely that solar energy conversion will provide a substantial portion of human energy needs ONLY if human settlements are designed to be highly efficient in their use of energy for comfort conditioning, lighting, mobility, production, communication, agriculture, and if the solar technologies can interface with the existing and emerging transmission and distribution infrastructures which will be associated with other sources of energy. (In this regard, the possibility of hydrogen becoming the next global fuel is especially attractive in that hydrogen pipelines and storage facilities can act as an effective buffer between the time varying output of solar conversion systems and the demands of settlements.)

There have been to date only a few attempts to evaluate the large scale solar option, and no attempts to evaluate it in terms of the impact on future courses of development in the developing parts of the world (primarily Asia and the Middle East). There is a strong need for an assessment of the long-term potential significance of a menu of solar conversion options which can permit comparison with the other three major alternatives, and which could serve as a basis for examination of strategies of mixed energy technologies (such as central station nuclear plants and dispersed solar and wind electric generation facilities, tied together in a common infrastructure). As an example, the various solar thermal electric power generation concepts can in principle be compared with geothermal, fusion and breeder reactors in terms of (among others) the following:

- Land use (problems of siting, impact on local ecosystems)
- Water requirements (cooling)
- Capital investment (dollars per kwe) and operation
- Materials requirements (tons of materials per Mwe)
- Energy investment (how long will it take for the plant to produce energy equivalent to the total energy invested in plant materials fabrication, construction, etc.)
- Infrastructure requirements-physical (requirements for new or existing pipelines, transmission lines, storage facilities, switching and programming systems, etc.)
- Infrastructure requirements-institutional (requirements for modification of established utility structure and practise, regulatory bodies and regulations, tax and investment structures, etc.)
- Social acceptability and public interest - impact on various implementation and diffusion scenarios
- Environmental impact
    - Air pollution
    - Water pollution
    - Thermal impact (including modification of local radiation via changes in albedo)
- Implications of various technologies (1000 MWe central station central vs. distributed small installations) on patterns of land use, transportation, human settlements, etc.

- System safety (nuclear issues are well in hand in studies; solar power plants using liquid Nak may present hazards, fires on homes with semiconductor power generators on roofs may present gas poison problems, etc.).

Solar Conversion, Energy Needs of Mankind and Implications for Land, Materials and Money

In most of the inhabited parts of the world, the average daily insolation is between 2.5 and 5 kwh(em) per square meter. This is roughly equivalent to 100 to 200 MW(em) per square kilometer AVERAGE solar power incident on a horizontal surface. Since the world population will inevitably reach some ten billion very early in the next century, we can ask the macroquestion of the land area implications of supplying energy via solar conversion to a large portion of the population.

$$10^{10} \text{ people at } 20 \text{ kw/person} = 2 \times 10^{8} \text{ Mw}$$

$$2 \text{ kw/person} = 2 \times 10^{7} \text{ Mw}$$

The technological optimists feel that we can (will?) reach the level of 20 kw per person sometime in the next century. Others, including myself, feel that a worldwide level of some 2 kw per person in most of the world can, through appropriate design of human settlements and their related infrastructures (agriculture, mobility, communications, etc.) provide a very attractive human environment. (I suspect that the argument over the relationship between levels of energy consumption and "quality" of life as a function of human settlement design and operation is destined to become one of the great issues of the coming fifty years).

If we were to provide all of the energy requirements for the upper level of consumption through solar energy conversion in the sunny* parts of the world (average daily insolation of 5 kwh_{em}/m^2) it would require (assuming an average solar conversion system efficiency of 0.2) about five million kilometers of land covered with solar conversion machinery. If such systems could be built for a total of $ $10/m^2$** to $ $50/m^2$ (including all storage, power conditioning, transmission, etc. reflected back into the initial investment), the total required initial investment alone (ignoring operation and maintenance) would be roughly ten to fifty trillion dollars or three to fifteen times the annual gross world product. Such an investment over a one century period would require (factoring out inflation) about three to fifteen percent of the 1974 gross world product per year. Assuming the systems weighed one to ten kilograms per square meter (light systems), the total weight would be roughly five to fifty billion metric tons of material. If construction took a century, the average

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*Assuming H_2 pipelines, long distance HU transmission lines etc.

**This corresponds to $ 100/kw to $ 500/kw.

required mobilization of materials would be some fifty to five hundred million metric tons per year. This can be compared with natural and mankind's mobilization of materials each year. (Ref: John Holdren, "Mankind as an Ecological Force", 1974).

Mobilization rates in metric tons per year

Materials	Geological rate	Mankind (mining and consumption
Iron	25,000,000	319,000,000
Copper	375,000	4,460,000
Zinc	370,000	3,930,000
Nickel	300,000	358,000
Lead	180,000	2,330,000
Phosphorus	180,000	6,500,000
Mercury	3,000	7,000
Tin	1,500	166,000
Aluminum	(JMW estimate)	6,000,000

At today's rates of mineral extraction, it appears that in even the lightest systems the majority of the materials in these systems would have to be steel; in view of the kinds of material mobilization and industrial production implications of the energy scenarios described in the MIT Energy Policy Study (Ref.) it will be difficult to increase world production of metals and finished products at the rate required by the optimistic saturation scenario for solar conversion. For 10 kg/m^2 systems, it is clearly an impossible situation.

Although this view is simplistic, it indicates the general order of the material issues involved. If we were to adopt the more modest proposition that over a one century period, the use of solar conversion equipment could grow to provide 20 per cent of the energy needs of a world of ten billion at 3 kw per person, the land required is reduced by a factor of 7 x 5 = 35 to 150,000 km^2. This is still a formidable area but the implications for materials mobilization and land use are now within a possible (I believe) range to consider. If, for example, some eight billion of the ten billion lived in low-rise dwellings with an average of 100 m^2 per ten inhabitants, the roof area available in principle for solar energy conversion would be 80,000 km^2 or about half of the total area required. Of course, the world's energy needs will exhibit very large spatial variations and most of the energy (in per capita terms) will be required in the very places where roof area is totally insufficient (dense cities). This suggests two things. First of all, it is likely that the optimum energy systems of the future will be mixes of nuclear and solar conversion systems, in the event solar is used on a large scale at all. Second of all, it appears that the total energy requirements of ten billion people will be determined within the 2 kw/person to 20 kw/person range by the patterns of future human settlements. It is then clear that evaluation of the solar option will require some evaluation of alternative future patterns of human settlements and the materials and energy implications of f these patterns.

However,,if a series of issues (inability of city growth to absorb most of the world's population growth, economic requirements for disaggregated populations, living on the land with intensive agriculture, etc.) converge to force most people to live in moderately low density settlements, much of THEIR energy could, it seems to me, be supplied from direct solar conversion in most of Asia, Africa, the Middle East and South America. The annual requirements of the mobilization of perhaps two million metric tons of material to construct the systems is at least compatible with future production of steel and perhaps aluminum. The active conversion elements, in the case of production of electricity by solid state means, will be either silicon (the second most abundant material in the crust of the earth) or direct band gap semiconductors (among other means) which require only a few microns of thickness. In these cases, it is likely that sufficient materials like Cd and S exist to permit large scale use of direct converters. The required information for evaluation of long-term large scale deployment is discussed in the section on investment requirements for the solar option.

Economics of Solar Conversion Systems

In the areas of the world most populated or likely to be highly populated over the coming century, the average daily solar insolation ranges from 2 - 3 kwh(em)/m^2-day in Northern Europe to 5 - 6 kwh(em)/m^2-day throughoutt southeast Asia and the Middle East. (Vienna varies from a low of 0.6 in December to a high of 5.3 in June and July, with an annual average of 3.0.) There is now evidence which strongly suggests that on a life-cycle cost basis (with investments amortized over 15 to 30 years, at 8 to 12%) some solar technologies can compete now or in the near future with electricity at 20 to 30 mils/kwhe AT the end user (such as buildings) for electric power, and can provide heat and air conditioning today at costs BELOW those associated in many parts of the world with electric resistive heating and oil heating, and with electric air conditioning.

Often the discussion of solar conversion economics takes the estimated costs of various systems as a starting point and then looks at the cost of delivered energy in comparison with the prevailing cost of local alternatives. A more general and straightforward parametric overview would be useful to create an economic framework in which any solar conversion system could be examined and compared with various alternatives.

The economic constraints can be determined by examining the following parameters:

kwh(em)/m^2-day (t)
Solar energy conversion efficiency
Use factor for energy produced
Amortization period and interest rate

Value of energy ($/MMBTU or mils/kwh) produced

The simplest economic analysis would assume that all harvested energy (say in the form of electricity) would be usable at all times during the year. By picking an overall system conversion efficiency (neglecting seasonal variations in efficiency), an amortization period and an interest rate, one can easily compute the $\$/m^2$ permitted investment in the TOTAL SYSTEM (all components, including storage, transmission, distribution and power conditioning reflected back into the unit cost) for the delivered energy to be competitive with the alternative at some price. To be specific, suppose one had in Vienna a system which converted sunlight into electricity with a 10% overall conversion efficiency, and which could be amortized at 10% per year for 25 years. The average solar insolation in Vienna is roughly 3 kwh(em)/m^2-day. 10% conversion to electricty would result in a total of 2737 kwhe over 25 years. If this electricity were worth an average of 10 mils/kwhe the total value would be $27.37 and the AVERAGE monthly value would be $ .091 permitting a total investment for the system of \$ 10.00/m^2 (maximum investment permissible, with no deductions for operation and maintenance).

By contrast, a system of 20% conversion efficiency operating in Jerusalem (roughly 6 kwh(em)/m^2-day) with electricity worth 30 mils/kwhe would permit, with the same investment structure, \$ 120./m^2.

Figure 1 indicates the relationship for a few examples between maximum permissible capital investment per square foot for a system. For example, consider the lowest line marked (20%, 0.5 ¢; 10%, 1 ¢). This indicates the maximum investment permitted per square meter for a system with a net conversion efficiency of 20% for energy worth a half cent per kwh or a system of ten percent efficiency producing energy worth one cent per kwh. Just to check this against other information we know that in the case of electricity, the usual investment structure for utilities results in the cost of electricity charged against capital plant investment at roughly 1 mil per kilowatt for each \$ 100 per kilowatt of installed capacity. Hence energy worth one cent per kilowatt hour would correspond, in this instance, to a plant investment of \$1,000. per kilowatt. In the example in Figure 1, 3 kwh per 24 hours, with a ten percent conversion efficiency, means that the maximum investment of \$ 10 per square meter corresponds to

$$\frac{\$\ 10}{3\ \text{kwh/day}} \times \frac{1\ \text{kw input}}{0.1\ \text{kw output}} \times 24\ \text{hours}$$

$$= \frac{10 \times 24}{.3} = \$\ 800/\text{kw}$$

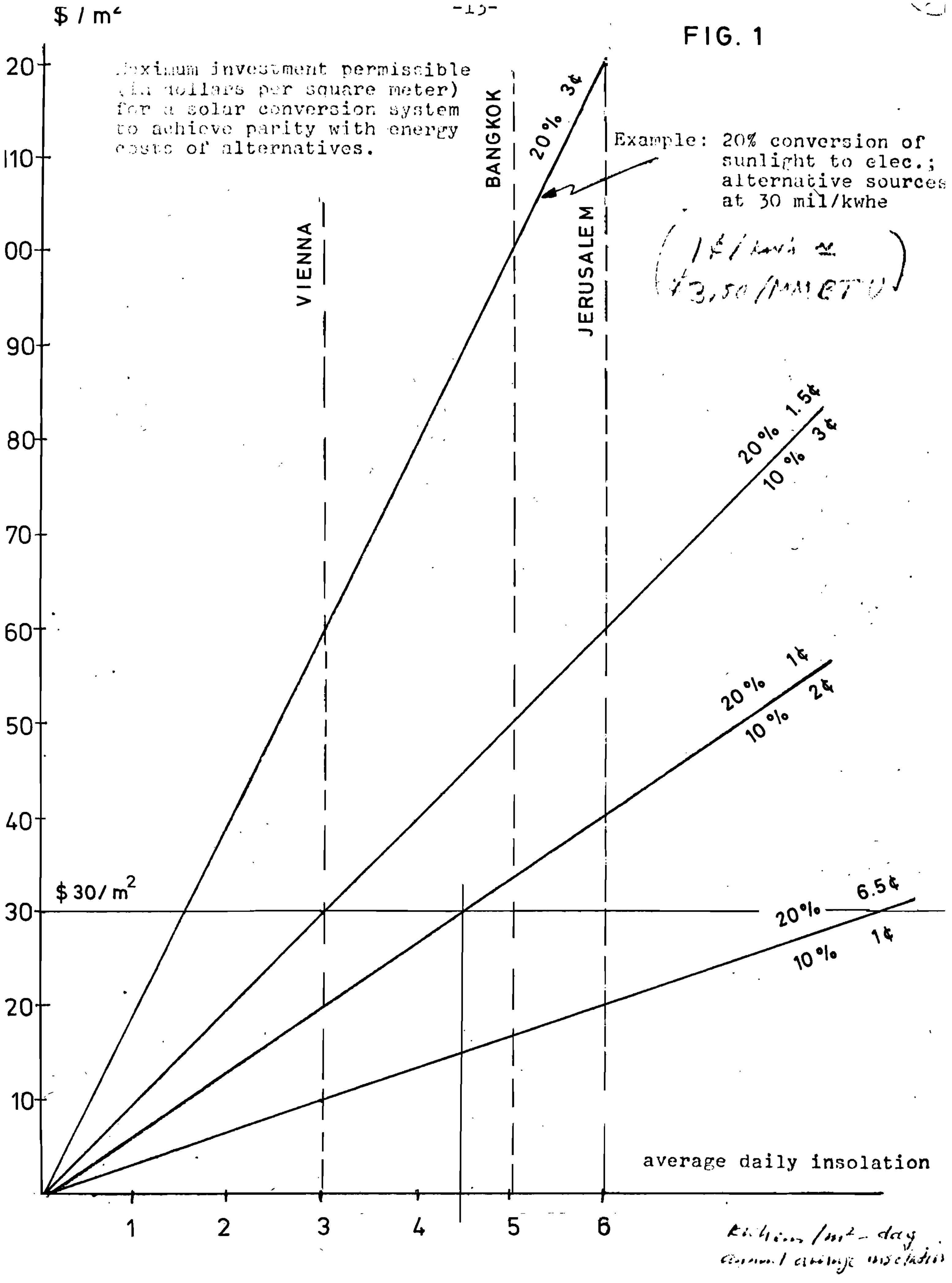
which is roughly the same (utility amortization rates are somewhat higher than the ten percent assumed in this rough calculation, which accounts for the difference).

Table 1 provides a few quantitative examples of this and Table 2 indicates the average daily insolation by month for five cities (including Vienna).

It seems likely, on the basis of recent calculations at Dupont, that direct conversion of sunlight to electricity by solid state means could be made possible with mass produced solar modules costing between $ 20 to $ 100 per square meter. Therefore, it seems likely that a practical and economically interesting solar electric conversion technology could be developed for many parts of the world. Obviously, far more sophisticated economic examinations must be made to evaluate specific technological options, but the economic goals appear within reach for many of the solar conversion options.

These examples are highly simplistic of course, but they do indicate the order of magnitude of the costs under consideration. A more detailed calculation would have to include the estimated costs of manufacturing, installing, maintaining and operating an electric utility system in which direct solar conversion elements were imbedded;

FIG. 1



Maximum investment permissible (in dollars per square meter) for a solar conversion system to achieve parity with energy costs of alternatives.

Example: 20% conversion of sunlight to elec.; alternative sources at 30 mil/kwhe

(1¢/kwh ≅ $3,50/MMBTU)

Table 1. Allowed Investment in Solar Conversion Systems for Various Levels of Insolation

Average Insolation*	Conversion Yield (10%)	kwhe/25 years	Value of yield at 10 mil/kwhe	Average monthly value	Allowed $/m^2 **
3.0	0.3	2737	$ 27.37	$ .091	$ 10.00
4.0	0.4	3650	$ 36.50	$ .122	$ 13.30
5.0	0.5	4562	$ 45.62	$ .152	$ 16.70
6.0	0.6	5475	$ 54.75	$ .183	$ 20.00

* Daily (annualized average) insolation, kwh(em) per square meter; computed from

information given in :
Lof, Duffie and Smith; "World Distribution of Solar Radiation", Solar Energy Laboratory
University of Wisconsin 1965

** Based on 10%/year, 25 year amortization

Table 2.

kwh(em)/m^2-day Annual average

	J	F	M	A	M	J	J	A	S	O	N	D	
Vienna	.80	1.52	2.57	3.85	5.03	5.31	5.31	4.53	3.21	1.85	.91	.59	2.96
Bangkok	4.98	5.66	5.26	5.63	5.63	5.26	4.52	4.68	3.54	4.45	5.33	5.05	5.06
Delhi	4.19	5.08	5.94	6.75	7.33	7.10	5.82	5.82	5.24	5.60	4.66	4.07	5.62
Jerusalem	3.38	4.20	5.30	6.82	7.84	8.57	8.41	7.86	6.74	5.28	3.75	3.05	5.94
Osaka	2.48	2.92	3.27	3.91	3.46	2.90	4.00	4.00	3.10	2.83	2.37	2.10	3.11

Daily insolation (taken from monthly averages) for Vienna, Bangkok, Delhi, Jerusalem and Osaka.
Calculated from data given in Lof, Duffie and Smith, "World Distribution of Solar Radiation", Solar Energy Laboratory of the University of Wisconsin, Report No. 21, July 1966.

All data shown in kilowatt-hours (electromagnetic) per square meter per day.

the lifecycle costs of all factors other than the capital investment would have to be deducted from the allowable investment per square meter.

Potential Contribution of IIASA

The significance of the solar option can be determined only after there is a careful examination of the total energy systems requirements for large-scale use of solar converters, including a determination of the requirements for the institutional and mechanical infrastructures which could support widespread use. The particular character of IIASA should allow it to make a strong preliminary exploration of this issue, drawing on extensive technical and economic work underway on specific solar energy technologies (primarily in the U.S., Japan, Israel and the USSR). The resident expertise in the area of evaluation of the nuclear option should facilitate the comparitive evaluation of extra-terrestrial and terrestrial nuclear power sources for the long term.

First of all, the special expertise in systems analysis would insure that a number of systems related issues would not be ignored. These include considerations of the electric system infrastructure and institutional system infrastructure requirements to permit large scale retrofitting of solid state solar-to-electric conversion modules on rooftops of existing buildings, as one example. Since the only interesting applications of solar energy conversion technologies will be applications on a very large-scale, the systems implications of various scales of deployment must be considered along with the considerations of engineering and economic feasibility on the micro-level.

A second important perspective which IIASA can bring is that of an international view of the potential role of large-scale solar conversion system deployment. In particular, the growing awareness of the critical links between resource-rich developing countries and the resource demanding industrialized countries should be reflected in discussions of the potential significance of developed nations assisting developing nations in introducing and diffusing the solar technologies.

A third aspect of the study will be the possibility of serious comparison of the solar and nuclear options. The IIASA expertise in the nuclear area will permit comparison on economic and environmental grounds and will also permit a comparison of the systems (infrastructure) implications of various nuclear and solar systems. An additional aspect which should be considered in any follow-on studies, would be an evaluation of a mixed system including central station nuclear power generation and dispersed solar-electric and solar-thermal power systems.

A fourth aspect of solar systems is related to the issue of energy transmission and distribution infrastructures. Since, in the case of large-scale solar thermal electric power generation (STEC), thermal storage to permit base load operation results in more than doubling of the installed cost estimates of 1000 MWe plants, the potential significance of the hydrogen economy in terms of practical use of solar conversion could be initially evaluated. This may be especially important in view of the fact that the National Science Foundation is pushing the concept of "tower power" as an early practical demonstration of large scale solar energy conversion. The concept involves mounting a thermal collector atop a 1500 foot tower, with a large array of flat steerable mirrors focusing solar energy on the collector. The absorbed solar energy could generate heat at temperatures sufficient to separate water into hydrogen and oxygen. In the event that hydrogen becomes the next widely used fuel in history, it is possible that such techniques for solar energy conversion would have their most economically interesting applications here.

IIASA should not attempt to duplicate the detailed engineering and economics studies being done elsewhere Those conducting such studies can become resources (contributors, consultants and reviewers) to input to the study. Rather, the emphasis of this study should be the strategic analysis of the potential significance of a menu of solar conversion system alternatives in terms of the contributions solar technologies can play on a large-scale, the issues facing the introduction and widespread and rapid diffusion of such technologies, and the definition of institutional and technical requirements which must precede such international diffusion. In particular, a first look at the systems implications for widespread use, would be a very important and unique contribution.

Finally, the personal contacts of IIASA personnel and leaders in government, education and industry could permit rapid communication of the key findings of this study in a way possibly far more effective than simply publishing the study without comment.

Program Objectives

The overall objectives of my present concept of an initial evaluation are indicated below. Undoubtedly they will go through some stages of iteration and modification in the months preceding the work and during the early phases of the work; however, I think the remarks in the paper cover most of the main points of concern. The objectives of the work include, it seems to me

1) A summary of the present state of the art of solar conversion technologies and an evaluation of the potential state of the art;
2) Evaluation of the economic, environmental, social and technical characteristics of a number of specific energy system options in which solar conversion plays a major or exclusive role, and comparison with nuclear;
3) Construction of scenarios for introduction and diffusion of various solar system options in a

number of locations (and cultures) around the world, including estimates of the fraction of human energy requirements solar conversion can supply as a function of time;

4) Identification of specific target areas of opportunity for industry, utilities and government for the introduction and diffusion of specific solar systems, and
5) Identification of institutional innovations which can speed the evaluation and introduction of solar systems (such as the creation of an International Solar Energy Agency, creation of bilateral and multilateral arrangements with the United States, the Soviet Union, Japan, Israel and Australia with other countries not having much solar conversion technology experience, pilot programs which could be sponsored by major foundations, such as Ford and Rockefeller, etc.);
6) Formulation of a comprehensive program (lasting perhaps 12 to 18 months, with six or so full-time team members) to create the first in-depth assessment of the solar option.

Systems for Initial Examination

In order to perform a useful study, the number of systems which can be examined must be limited, along with the number of potential types of sites. Some of the areas most likely to be fruitful, in my opinion, include:

1) Energy conservation in buildings through the use of solar water heating and space conditioning (thermal systems, turbines, heat pumps);
2) Direct conversion to electricity ("solar cells")
   a) systems for buildings (independent or interconnected)
   b) small "central station" power generation (100 kw to 10 Mw);
3) Wind generation systems of various sizes up to 5 Mwe;
4) Solar-thermal-electric conversion from 10 kw to 1000 Mw
   a) peaking only
   b) no storage, hydrogen and oxygen production
   c) base load with thermal or electrical storage;
5) Photosynthetic production of fuels;
6) The Glaser orbiting solar power station (a review of the intensive study already done, no new work at IIASA on the technology).

Also, some look at mixed systems would be useful. For example, in countries which are water-poor, near the ocean and have abundant sunshine (Israel and Mexico) the combination of solar thermal power generation and thermal desalination may be attractive. A 1000 Mwe solar power plant of 20% thermal efficiency will require the equivalent of 40,000 acre feet per year in evaporative cooling so this may turn out to be an option worth exploring).

Establishing a Review Policy

It is clear that any preliminary report in the area of evaluating large-scale energy alternatives, including the solar option, can benefit greatly from informed and critical review. I would propose that a review cycle be established as part of the process of preparing the initial external report on the solar option. The review steps might be:

Step 1: Review and modification by the solar energy task force.

Step 2: Review by the energy group and modification by the solar group.

Step 3: Review by the entire IIASA staff and modification by the solar group, internal publication of draft.

Step 4: Review by an international panel of experts in relevant areas, and final revision and editing by solar group.

Step 5: Publication as an external IIASA report.

I have drawn up an ad hoc list of possible reviewers, based on my personal acquaintance with people interested in the subject and sufficiently informed to make critically useful comments. Obviously the selection of a final review group will require some sort of collective judgement by members of the involved IIASA staff, and this list should be considered as a point of discussion and departure only.

An ad hoc List of Potential Reviewers - IIASA Solar Assessment

Nation	Reviewer
Israel	Dr. Harry Svi Tabor National Physical Laboratory of Israel
Iran	Dr. Taghi Farvar Department of the Environment, Tehran
	Dr. Mehdi Bahadori Pahlavi University, Shiraz
Greece	Dr. A. Hatzikakidis Scientific Society of Solar and Aeolian Energy
	Mr. P. Psomopoulis and Dr. C. Doxiadis Athens Center for Ekistics
India	Dr. V.G. Bhide National Physical Laboratory, Delhi
France	Dr. Felix Trombe CNRS - Odeillo
USSR	Dr. Yu. N. Malevsky Krshizhanovsky Institute of Power Engineering - Solar Energy Laboratory
	Academician N.S. Lidorenko All-Union Institute on the Source of Electricity, Moscow
	Dr. B.V. Tarizevsky All-Union Institute for Research in Solar Technology
	Academician V.A. Baum, Director Physical Institute of the Academy of Sciences of the Turkmenian S.S.R., Ashkabad
	Dr. J.T. Shermasian Academy of Sciences of the Armenian S.S.R., Erevan
Australia	Roger Morse, CSIRO

USA
(partial list)

Prof. Melvin Calvin
U. of Calif., Berkeley

Prof. Marshall Merriam
U. of Calif., Berkeley

Prof. Lester Lees
Environmental Quality Laboratory,
Caltech

Mr. Ab Davis, Jet Propulsion Laboratory,
Caltech

Mr. R. Caputo, JPL, Caltech

Prof. Karl Boer
Univ. of Delaware

Prof. Martin Wolf
Univ. of Pennsylvania

Dr. Lloyd Herwig
National Science Foundation

Mr. William Woodward
NASA Headquarters

Prof. Hildebrandt
Univ. of Houston

Dr. Piet Bos
Aerospace Corporation, Los Angeles

Prof. John Holdren
Univ. of Calif., Berkeley

Prof. George Lof
Colorado State University

Prof. Jack Duffie
Univ. of Wisconsin

Dean Harvey Perloff
Prof. Richard Schoen
UCLA School of Architecture and
Urban Planning

Mr. P. Richard Rittelman, architect
Butler, Pa.

Mr. Robert Reines
ILS Laboratories, Albuequerque

USA (cont'd)	Prof. Erich Farber Univ. of Florida
	Dr. Sheldon Isakoff Du Pont Corporation, Wilmington, Delaware
	Mr. John Yellott, Phoenix