Solar Energy Task Progress Report for 1975/76: Evaluation of Solar Energy Options

Bell, C.R.

IIASA Research Memorandum
May 1977

Bell, C.R. (1977) Solar Energy Task Progress Report for 1975/76: Evaluation of Solar Energy Options. IIASA Research Memorandum. Copyright © May 1977 by the author(s). http://pure.iiasa.ac.at/795/

RM-77-20

SOLAR ENERGY TASK PROGRESS REPORT
FOR 1975/76
EVALUATION OF SOLAR ENERGY OPTIONS

Charles R. Bell

May 1977

PREFACE

The IIASA Energy Program includes assessment of solar options as a potential long-term energy supply for various regions of the world, where solar energy utilization may become a growing part of the energy **mix**.

Energy assessment in the 1975/76 time period concentrated on solar-thermal systems and photovoltaic systems. The state of the art in these areas is still in a formative stage, creating a wide range of uncertainties that prevail in the performance and economic aspects of these options.

An attempt to validate the key parameters in this field will continue at IIASA through 1977. This interim report summarizes the principal solar-thermal and photovoltaic options in terms of contemporary technology and identifies a composite of the critical economic parameters for the subject options and estimates of the corresponding area requirements.

ABSTRACT

Solar options are evaluated as a potential source for meeting future energy supply requirements. Emphasis is on contemporary concepts in the solar-thermal and photovoltaic systems and their space, as well as economic constraints.

The range of uncertainties during this formative stage of solar technology is shown in typical examples of performance and cost estimates. The broad spectrum of assessed information is synthesized and condensed for general information as an interim report. The fundamental trends of the continuing efforts in the subject field are identified.

SUMMARY

The solar energy options for partially meeting the future global energy demand, and the strategies for their embedding, are studied at IIASA as a part of the global energy assessment. The solar options that have been evaluated during 1975/76 are based on presently available (global) insolation values (solar energy inputs). Solar energy conversion system alternatives were assessed that range from low-temperature concepts for water and space heating to thermal-electric and photovoltaic concepts for large-scale generation of electricity. Overall system efficiencies from 7 to 22 per cent for the electric power generating systems, or from 30 to 60 per cent for the space and water heating systems (from available sources) were evaluated, and composite estimates were made.

Conceptualization of insolation, siting, energy conversion, and electric power integration was based on reviews of contemporary solar energy technology assessments. Major solar energy conversion concepts were evaluated in terms of their embedding potential and integration in future utilities distribution networks. Capital, materials, and manpower diversion issues were considered in terms of the current state of the art of solar energy conversion technology.

The regional solar energy projects at IIASA started with the Austrian case study, the experiences from which are being applied to evaluate the solar energy utilization potential in the Federal Republic of Germany. Both of these regional studies are being synthesized as examples of models for future use in the global energy study. Energy storage issues are considered in these evaluations.

The solar energy conversion potential for developing countries is being evaluated on the basis of known energy options and possible embedding strategies, including energy demand projections and compensation trade considerations, commensurate with local capabilities.

The summary of the IIASA Solar Energy Task effort in 1975/76 is concluded with an outline of recommendations for the 1977/78 time period, concentrating on the global potential of solar options, probable supply and demand scenarios, and the envisioned feasibility of embedding strategies. At this time, it is apparent that premature large-scale implementation of solar options may adversely affect their long-term acceptance because the performance of the contemporary solar systems may prove marginal. More favorable market penetration conditions will develop as more efficient systems become available in the future.

TABLE OF CONTENTS

I. INTRODUCTION

Utilization of solar energy for meeting part of the future energy demands on the global scale is subject to accelerated research and developments in most industrialized countries. Currently, solar options are envisioned as fuel-conserving potential in most of Europe, and in the United States, and possibly as viable energy systems for the developing countries. It is anticipated that the rate of transition from nonrenewable fuels to renewable energy sources will be stimulated by decreasing availability and increasing cost of fossil and nuclear fuels. However, because of the contemporary uncertainties about the overall performance of the various solar options, the evaluation of solar energy conversion concepts during 1975/76 had to be limited to approximations and projections based on composites from current research work in the countries of IIASA's National Member Organizations. An attempt was nevertheless made to develop some approximations for preliminary regional and global energy studies.

This progress report does not attempt to summarize all the studied data; it reflects primarily the quantitative highlights and synthesis for large-scale application of solar options. Time and resources limitations necessitated to restrict the study to solar-thermal and photovoltaic concepts. It is realized that estimates on solar energy conversion, based on first-generation conceptual designs, are not necessarily valid for energy mix projections over an extended period of time. Innovative developments in solar energy collection, superior heat-transfer fluids, mass production of photovoltaic cells, energy storage, and in other critical areas will probably provide a foundation for more competitive solutions in the future.

II. SOLAR ENERGY AS A RESOURCE

The gradually decreasing availability of fossil fuels, their increasing cost, and their impact on our environment is stimulating research for more effective and efficient ways of harnessing solar energy. The need to develop timely large-scale applications of solar energy, with a minimum of perturbation to the economic and social systems, necessitates careful evaluation of solar options and development of methodology for their gradual integration in the regional and ultimately global energy supply efforts.

A "solar option" is viewed as a solar energy conversion system, capable of transforming sunlight into useful forms of energy, such as heat, shaft horsepower, electricity, and synthetic fuels. The two categories of solar energy conversion receiving attention on global scale are:

(a) indirect conversion in the biosphere (winds, rains, waves, thermal gradients of the ocean, etc.) followed by conversion by man-made machines (windmills, hydroelectric power plants, wave motion rectifiers, ocean-thermal systems, etc.);

(b) direct conversion, using thermal collectors, producing heat and/or electricity (e.g. heating air or water, and/or producing steam for turbo-generators), or using photovoltaic cells for direct production of electricity and possibly hydrogen. Photosynthesis and solar chemistry also belong to this category and might prove valuable in the future.

The solar energy task at IIASA initially concentrated on the system studies of direct conversion of solar energy (mostly direct irradiance) to heat and on a variety of thermo-dynamic pathways for the production of electric power, because these do not require major technological advances and thus offer an earlier application for large-scale systems. Photovoltaic concepts (solar cells) were considered because of their long-term potential and their ability to convert both direct and diffuse solar energy to electricity. Some significant advances in the development of mass-produced solar arrays (fully encapsulated solar cells with protective circuitry) are conceivable within ten years, which would permit highly flexible integration of such arrays in urban and in rural environments.

The useful solar energy inputs (direct and diffuse insolation) that are viewed as a convertible resource on the earth's surface average from about 1000 kWh(th)/m^2 and less than 1500 hours of direct sunshine per year (e.g. in regions near 55^o latitude), to over 2300 kWh(th)/m^2 and over 3000 hours of direct sunshine per year (e.g. in some desert regions near 20^o to 30^o latitude). The practical conversion potential of such energy levels is subject to several screening procedures that aid in identifying the advantageous options and suitable sites. Large regions of Africa, Southwestern USA, Asia, Australia, and South America have very favorable locations for solar energy conversion facilities. The preliminary identification of solar options is based on insolation values (Table 1 [Ref. 1,2,3]), and on the availability of energy storage and backup capabilities (all subject to further optimization processes). These insolation levels are composites of the peak values (when the sun is at least 30^o over the horizon, and at early morning as well as late afternoon hours, with both direct and diffuse components).

The screening procedures for the electric power (high temperature) options are primarily focused on the following criteria:

(a) insolation levels: annual distribution of effective (direct) solar insolation, related energy storage requirements, and integration into existing network;

(b) competitiveness and compatibility with other electric power systems;

(c) land (and/or urban areas) availability and suitability (orientation, elevation, slope, proximity to hydro-storage possibilities, etc.);

(d) access to water, utilities network, road, rail, etc.;

(e) legal issues: value, shadowing, ownership rights, etc.;

(f) ecological and meteorological characteristics (weather patterns, exposures, etc.).

Table 1. Approximate delineation of applicable solar options for given insolation levels

Insolation Levels[a] and Equivalents[b]				Average Overall Conversion System Efficiency		Typical Option and Region[d]
Langleys per day	$\frac{W}{m^2}$[c]	$\frac{kWh(th)}{m^2}$.day	$\frac{kWh(th)}{m^2}$.year	(th)	(e)	
538	261	6.25	2300	0.60	0.20	Electric power and fuel product A,B,C
512	248	5.95	2190	0.55	0.18	Electric power; industrial process heat; cooling D,E
427	207	4.96	1825	0.50	0.15	
274	133	3.19	1163	0.40	0.08	
256	124	2.97	1095	0.37	--	Air and/or water heating E
171	83	1.98	730	0.30	--	

[a] averages of measured global radiation values on horizontal surface (direct and diffuse); proper angular orientation of the collectors yields significantly better energy inputs (see Table 4);

[b] see conversion table;

[c] annual 24 hours/day averages;

[d] regions: A as in primary regions of North Africa and Southwestern USA; B as in South America and Australia; C as in Asia and Australia; D as in secondary regions of North and South America, and primary regions of Europe; E as in regions near 50° Northern latitude.

The presently available insolation values are generally global irradiance records on horizontal surface (Table 4), without separation of the diffuse and direct components. Solar energy conversion in thermal systems depends primarily on direct irradiance (sunshine) at near-peak hours. Solar-thermal conversion concepts with concentrating features (such as solar-electric systems) can use only the direct component of insolation, and their effectiveness is highest during peak hours (where the sun is at least 30° over the horizon. Simple application of insolation levels, such as in Table 1, could therefore be misleading because a solar energy conversion system is also subject to a daily start-up phase, during which certain equilibrium temperatures of the system must be reached before it can deliver its design performance, or a certain amount of heat must be stored to shorten the start-up phase. The characteristics and uncertainties of solar energy inputs are of lesser impact in the favorable regions (over 2300 $kWh(th)/m^2 \cdot a$, and over 3000 hours sunshine per year. In the marginal regions, like Central Europe, however, very close screening procedures will have to be developed for feasibility considerations of the applicable options.

The screening procedures for the space and/or water heating options (low temperature, below ≈100°C) are, of course, similar to those for electric power options, but with more emphasis on area constraints on buildings, alternate solutions, and economic constraints.

On a global scale, the system efficiencies of solar-electric power options (high temperature, above ≈300°C) are brought into focus for evaluating solar energy as a renewable resource, free of fuel supply problems, and with a relatively favorable energy payback time. The parameters considered for such assessments are:

(a) overall conversion system efficiency, η_c, attainable (see options in Table 1), specifically optimized for the location identified by screening procedures;

(b) plant capacity factor, f_r, expressed as the ratio of annual operating hours and maximum hours per year, for example, 2500/8760=0.28 for hybrid and/or peaking versions of solar plants without external energy storage (see Table 6), or 6000/8760=0.68 for base-load power plants with adequate energy storage, thus comparable to conventional power plants.

(c) area utilization factor, f_a, (or ground cover ratio), equal to the ratio of the effective collectors' area to the total area used for a given plant. Typically, f_a may range from 0.35 to 0.50, depending upon the average of the varied spacial distribution of the collectors, and the topography of the site (i.e. favorable slope). It assures operating space, safety, and maintenance access.

(d) energy storage efficiency, η_s, which for large-scale hydrostorage systems averages 0.70 (turn around), and could be met at a comparable level with future hydrogen production and storage, and/or other advanced systems (see Table 7). For a base-load STEC[1], η_s of 0.7 would be up-graded to 0.8 for systems consideration, because only that part of energy is stored which will be used during "no-sunshine" hours.

Pragmatic evaluation of solar energy as a resource for the low temperature solar options depends upon the success of developing effective absorber surfaces for the collectors (in the next three to five years), and decreases their market price without compromising operating life (exceeding amortization time). Pragmatic evaluation of solar energy as a resource for the high temperature solar-electric options depends upon the success of further developments in the next five to eight years, and hopefully cost reduction of the solar energy collecting systems, as well as on the identification of available inexpensive land areas that would not require costly access.

A typical land demand approximation for pure solar-electric plants (base-load versions), derived with a typical system performance profile, normalized to a plant capacity factor (f_p) or 0.68 (to permit comparison with conventional and/or nuclear plants) and with a turnaround energy storage efficiency (η_s) of 0.7 for the hours without sunshine, yields the estimates in Table 2.

$$A_t \approx \frac{8760\, f_p}{I_h\, \eta_c\, \eta_s} (1/f_a) \qquad (1)$$

where A_t = total area required (m^2/kW(e));

I_h = insolation estimate (on horizontal surface). (kWh/$m^2 \cdot$a)

Of course, a significant reduction of site area is realizable for more favorable insolation regions, and for hybrid installations (see Section III and Table 5). Topographic features of the site, such as favorable slope, can enhance the reduction of area requirements. Furthermore, in some cases multiple use of land can be envisioned (i.e. agriculture), and in the future development of urban areas, some esthetically attractive integration with other structures appears feasible. Since the photovoltaic systems have η_c of 0.10, their land area requirements are comparable to the low performance STECs.

---

[1] solar-thermal-electric conversion

Table 2. Typical land area required for large-scale solar-thermal-electric plants, 100 MW(e) base-load, with area utilization factor 0.37(f_a)

Overall System Efficiency (η_c)	Insolation Levels (I_h)[a] (kWh(th)/m^2 per year energy input)		
	1000	1500	2000
0.10	20.1	13.4	10.0
0.20	10.0	6.7	5.0

[a] as available insolation data relate to measurements on horizontal surface, an increase due to two-axes tracking would be required. To avoid complexity, for the approximation a higher overall system efficiency estimate is used instead.

Closer investigation shows that, although the land area requirements for the siting of solar-electric plants are substantial, they would be well under two per cent of the land area in most regions where it would be desirable to apply solar options for meeting all future demands.

More visible constraints are the capital and materials demands for such large facilities. Although accurate design information was not available, a composite of approximations for a heliostats field with a central receiver tower shows that over 45 kg/m^2 of industrially significant materials is required (concrete can, by design, substitute part of the weight); this means about 45,000 tons[2] per km^2 of effective collector surfaces--to be erected for next generation concepts--or about 83,250t for the 5 km^2/100MW(e) site. This indicates that for large-scale application of solar options, a rather sizeable diversion of materials and capital will be required (see Tables 6 and 10). These relationships will be further analyzed during the 1977 time period.

The critical issue remains to be energy storage for geographic areas with highly fluctuating insolation values during the winter months, without suitable hydrostorage, and

---

[2] t means metric tons throughout this paper.

without adequate backup electric power generation by conventional methods (see Table 7). In such areas, the use of liquid hydrogen as energy storage medium and/or synthetic fuel appears to be an attractive long-term solution. In some locations the solar and the wind energy conversion potentials complement each other on an annual basis, thus minimizing energy storage requirements for continuous operation (further energy storage considerations are in Section III). Again, however, a major capital diversion would be required for the construction of such dual facilities.

A realistic comparison of solar energy--as a resource for generating electricity--with plants using fossil fuel and nuclear fuel should be based on work performance (i.e. MWh delivered) rather than on power performance (MW rating), because of the distinctly different operating time and performance characteristics of the solar plants. Because the future cost of generating electricity will significantly influence the acceptance of solar energy conversion as a viable resource for meeting an increasing portion of the future energy demand, a conceptualization of the governing parameters is outlined in Table 3. There is, of course, always the possibility of technological breakthroughs that would enhance an accelerated use of solar energy conversion as a major resource for regions where the nuclear and/or coal options will not meet the projected energy demands.

The global drive for renewable, clean energy supply, aiming ultimately at three to five kW energy mix per capita, places solar energy as a significant resource, capable of meeting a part of the future energy demands if the capital, materials, and manpower diversion issues can be resolved. In locations with favorable insolations, about 1.25 m^2 of collector surface may yield an electrical energy equivalent of one barrel of oil per year, with current technology. The anticipated future progress in producing and transporting hydrogen would therefore suggest development of solar energy-operated hydrogen production and liquefaction facilities in the favorable insolation regions as a method of converting solar energy to a practical energy resource.

III. TECHNOLOGY ASSESSMENT REVIEW

The continuing process of information acquisition and validation of the IIASA-Solar Group is creating a data base on a global scale, while working relations with key institutions are established. There is a significant variation of quantitative data on many critical subjects, which stipulates a need to dedicate more effort to the validation of the acquired data and, wherever possible, to the development of a workable agreement between the theoretical, experimental, and operational values.

Table 3. Some of the key parameters affecting future electric power generating cost

Parameters	Fossil and Nuclear Plants	Solar Options
Fuel cost and availability	Cost increasing, and scarcity certain	No fuel needed
Waste disposal and storage	Problems of growing proportion	None significant
Pollution con-control requirements	Becoming more stringent, thus more costly	None
Plant performance limitations	Subject to availability of high-grade fuels, and effectiveness of pollution controls	Operation only during hours of direct sunshine
Energy storage requirements	None for contemporary plants, but as nuclear plants share increases, storage is probably needed to meet peak loading demands	None or low for hybrid systems, but very high for base-load systems
Benefits of technological progress	Improved pollution controls, more cost-effective waste disposal, and proven FBR (fast breeder reactor) and/or fusion reactors would accelerate acceptance	Better working fluids for the STEC[a] versions, or mass-produced, low-cost photovoltaic arrays, as well as cost-effective energy storage systems would enhance utilization
Impact of capital requirements	Currently acceptable, but with increasing negative effects, due to cost of anti-pollution and safeguards equipment	Unfavorable, because of high initial investments
Impact of inflation	During construction, as well as during operation due to cost of fuel, antipollution measures, and waste disposal requirements	Mainly during plant construction, but decreasing during operation, as neither fuel nor pollution safeguards needed
Impact of materials requirements	Not significant for fossil-fired plants, but relatively high for nuclear power plants	Significant requirements of materials and possibly spares

[a] solar-thermal-electric conversion

The large-scale system aspect studies provided first approximations of solar energy conversion criteria in general. An Austrian case study (further described in Section IV) was performed that used synthesized insolation values and reviewed applicable energy conversion systems. It included economic scenarios with oil prices projected up to $15/bbl, and with interest rates up to 12 per cent [Ref. 4,5]. **The overall efficiencies of the evaluated** solar options for producing electricity range from about seven per cent (fixed position, flat-plate collectors) to 22 per cent (heliostats field and central tower receiver) in favorable insolation regions (see Table 6). Design optimizations and improved working fluids for heat transmission may produce even better overall efficiencies. However, the major problems in evaluating solar energy conversion pertain to regions of lower insolation, where the number of effective sunshine hours is subject to irregular variations. Significant differences of insolation values are also due to collector positioning during various parts of the year. Table 4 provides an example from a location near Phoenix, Arizona (≈33°N) [Ref. 3].

Table 4. Measured insolation, energy input, on collectors at various positions

Solar Collector Positioning (at 33°N)	Measured Insolation[a]			
	kWh(th)/m^2 per day			kWh(th)/m^2 per year
	Dec. 21	June 21	August 21	
Horizontal (fixed)	2.95	7.00	4.97	2056
Set at latitude tilt	5.37	5.91	5.64	2300
With two-axes tracking	6.01	9.68	8.39	3304

[a] composite of direct and diffuse irradiation. Note that concentrating collectors can only convert direct solar irradiation.

A fixed collector at latitude angle tilt receives, at the sample location, almost 12 per cent more energy than a horizontal one, and a two-axes tracking collector nearly 60 per cent more energy. Validation of such data for other locations have not been available so far. These differences require that the solar energy conversion systems must be carefully tailored to the insolation characteristics of the location under consideration, land availability, materials demands, economic considerations, and environmental impact.

Concepts of solar-electric plants with heliostats (mirrors) field and central receiver tower (i.e. the principal STEC version) were considered first in hybrid configuration, combined with conventional power plants [Ref. 4, 5, & 6]. Such a configuration would not require a large energy storage capacity; it produces steam by concentrated solar energy conversion during sunny days, running the turbo-generators of the conventional power plant, thus saving significant amounts of fuel. The internal energy storage in the primary heat-transfer fluid of this plant provides for operating continuity when clouds produce shadow over the heliostats. The heat stored in the working fluid maintains steam-producing capability for 0.5 to a few hours, depending upon design. This necessitates certain performance trade-offs, because the steam flow cannot equal the turbine capacity for all the sunshine hours, some of which must be used to maintain the operating temperatures of the system and charge up the energy storage. Because the early morning and late evening sunshine hours do not provide the energy input characterized by the "peak hours" (when the sun is at least 30° over the horizon), the quantitative assessment of such plants for various locations is somewhat speculative.

A well-defined version of a 100 MW(e) solar-electric plant with heliostats field and central receiver tower was proposed by Aerospace Corporation [Ref. 6]. It is given in four basic configurations (Table 5). The assumed location is in the desert region of Southwestern USA, where the average insolation values exceed 2300 kWh(th)/m^2 measured on horizontal surface and over 3000 sunshine hours per year. Internal thermal energy storage (≈\$15/kWh) is envisioned in all these configurations. The near-optimum location would make an integration with utilities network practical (for example, the electric power demand trends for air conditioning favorably correlate with available insolation values), and a limited demand of energy storage feasible.

The 100 MW(e) central receiver concept was utilized as a typical model solar-electric power plant for locations with favorable insolation values and proximity to an existing utilities network. The multi-module concept, with a 1.3 km^2 area modules (subject to required configuration) facilities adaptation of relatively low receiver towers of tower ≈260 m height for each module), and a variety of load configurations, which respond to a multitude of solar power-plant integration requirements into the existing network (see also Figure 1 in Section V).

Table 5. 100 MW(e) central receiver concept versions (≈2300 kWh(th)/m^2·a and over 3000 hours of sunshine per year)

Configuration	Total Area (km^2)	Heliostats Area (km^2)	Internal Energy Storage (hours)
Hybrid (daytime)	1.3	0.5	0.5
Peaking (daytime)	1.3	0.5	3.0
Intermediate	2.6	1.0	6.0
Base-load	3.9	1.5	12.0

During the 1975/76 technology assessment review, the Aerospace Corporation concept [Ref. 6] was compared to a number of alternate proposals [Ref. 7, 8 & 9], and an overview was made (Table 6) for comparative evaluation of the principal solar-thermal and photovoltaic solar energy conversion systems. The composite of the estimates from the various (1973/75) sources was normalized to a hybrid "daytime only" configuration, to eliminate variation caused by widely different external energy storage concepts for meeting specific local network integration requirements. Furthermore, a location with insolation exceeding 2300 kWh(th)/m^2·a (with over 3000 hours of sunshine per year), and normalized 1975 US $ cost estimates were used merely to facilitate a relative comparison of the systems. The economic estimates were adjusted to 15 per cent annual fixed charge, a 30-year amortization period, and operations and maintenance charges (O&M) that were derived from correlation analyses with relatable power plant systems (≈10 to 20 mills/kWh).[3] The estimated cost of generating electricity (C_e) was based on the simplified expression;

$$C_e \approx \left(\frac{I_t c_f}{8.76\ f_p}\right) + m \quad , \qquad (2)$$

where C_e = cost of generating electricity (mills/kWh(e))
(1 mill = $ 0.001)

---

[3] conventional power plants have O&M charges below 2 mills/kWh.

Table 6. Comparison of 100 MW(e) "daytime only" solar energy conversion systems without energy storage (in high insolation areas of the world)

Collector Concepts / Parameter Estimates[a]	Flat Plate	Two Dimensional Trough	Paraboloidal Dish	Heliostats & Central Receiver	Photovoltaic Arrays
Approximate site (km^2)	5.0	2.1	2.0	1.3	4.5
Sun tracking	None	1-axis	2-axes	2-axes	None
Water requirements[b]	Yes	Yes	Yes	Yes	None
Collector (S/kW(e))	1525	920	650	600	1100
Receiver (S/kW(e))	-	280	50	170	-
Energy transport ($/kW(e))	180	250	150	50	80
Power conversion ($/kW(e))	260	200	200	160	100
Other (incl. land) (S/kW(e))	100	100	100	100	150
Capital investment (S/I_tkW(e))	2065	1750	1150	1080	1430
Plant load factor (%) f_p	0.20	0.25	0.28	0.28	0.33
Overall efficiency (%)	0.07	0.15	0.20	0.22	0.10
Availability (year)	1977	1980	1980	1980	1985
Electric power generating cost (mills/kWh(e))	197	140	80	76	84

[a] composite of estimates (1975 US $ direct capital cost);

[b] as working fluid and/or for cooling.

I_t = estimate of capital investment (\$/kW(e));

c_f = annual fixed charge rate estimate (%);

f_p = plant load factor estimate (%);

m = operations and maintenance cost estimate (mills/kWh(e))

In the absence of external energy storage capacity, such systems are viewed as complementary hybrid facilities for electric power producing complexes, conceived to attain significant savings of fossil fuels. These preliminary estimates are for comparison only.

Examining the data in Table 6, it is apparent why the "heliostats with central receiver tower" concept represents the currently preferred system for a moderate size (≈50 to 100 MW(e)) power plant (a prototype version is under construction at Sandia, New Mexico, USA):

(a) Flat plate collectors are non-concentrating, and feature relatively poor performance (low operating temperatures) for generating electric power. They have high demand on materials (piping, insulation, flow control elements, etc.), and a probably low overall reliability with the attendant high maintenance cost.

(b) Two-dimensional troughs have the fundamental disadvantages of the flat plate collectors, but are capable of concentrating solar energy. They therefore produce much higher temperatures (≈400°C or more) and, consequently, a much better overall performance.

(c) Parabolic dish collectors require a higher level of technology. They inherently have a poor area utilization factor, but could produce high enough temperatures (≈1500°C or more in favorable locations) for advanced concepts of hydrogen production.

(d) The heliostats field with central power receiver appears to be optimum for this category of power plants (preferred STEC). It has a relatively lower demand for materials and, with its high concentration ratios, it has good working characteristics that are compatible with those of conventional turbo-generators.

(e) Photovoltaic arrays might become competitive around 1985 if the current development efforts result in low-cost mass production of solar cells and their encapsulation methods. The operating characteristics are further enhanced because the diffuse as well as the direct solar radiation are useful.

All the concepts except the photovoltaic array can benefit in the future from the developments of high performance working fluids; and all of them would gain from the developments of low-cost, efficient energy storage systems. Low cost of land would also make a significant contribution.

Depending upon the future developments of oil prices, it can be argued that, while stricter pollution controls and increasing cost of fuels will cause increases of electric power generating cost in conventional power plants, the future development trends of solar-electric power plants--which have no need for fuel and thus create no significant pollution problems--may gradually yield a competitive cost of electricity. Quantitative information for a reasonable development of this hypothesis has not been available so far.

Table 7 summarizes the contemporary state of the art of energy storage systems [Ref. 10 & 11]. It is a composite of obtained information, and the economic data are normalized to 1975 US dollars; they are for use in relative assessments only.

The cost of the incremental increase in busbar cost of generating electricity for energy storage can be evaluated by the following simplified expression:

$$C_s \approx \left(\frac{I_s c_f}{8.76\ f_s\ \eta_s}\right) + m_s \quad , \qquad (3)$$

where C_s = incremental cost of energy storage (mills/kWh(e));

I_s = estimate of capital investment for energy storage system ($/kW(e));

c_f = annual fixed-charge rate estimate (%);

f_s = load factor estimates (%);

η_s = turnaround efficiency for the storage system (%);

m_s = operations and maintenance cost estimate (mills/kWh(e)).

Two methods of capital investment estimates are shown: capital investment ($/kW(e)) for large storage capacities in the multi-MW(e) range; and capital investment for medium storage capacities, where $/kW(e) is added to $/kWh(e) times average hours of energy delivery from storage per day. For example, evaluating for pumped hydro and liquid hydrogen, the estimates are 10 and 12 mills/kWh(e), respectively.

Table 7. Energy storage systems assessment (approximations)

Concepts Characteristics	Pumped hydro-storage	Electro-magnetic (cryogenic)	Thermal	Liquid hydrogen (with fuel cell)	Advanced flywheels	Compressed air (adiabatic)	Batteries (Pb-acid)
Typical, economic module size, MWh	100	500	20	1 +	1	10 +	1
Minimum economic size for utilities, MWh	10000	10000	600	10	10	80	10
Dispersed storage capacity	no [a]	no	yes	yes	yes	yes [a]	yes
Average performance, kWh/kg			0.12	38 +	0.08		(200W/kg) 0.02
Turnaround efficiency, percent	75	90	80	60	85	60	75
Estimated rate of loss, percent/d			5 to 10	0.3 - 0.8 (boil-off use)	0.5		0.1 - 0.2
Estimated capital investment, $/kW	250	550	350	300	400	230	180
b	(80+)	(50+)	(200+)	(230+)	(45+)	(100+)	(100+)
Estimated investment, $/kWh b	(+10)	(+300)	(+8)	(+8)	(+65)	(+15)	(+35)
Expected system life, years	50	30	20	30	30	20	15
Estimated earlier availability	now	1995	1982	1985	1985	1982	now

a subject to topography and/or geological constraints.

b for large storage capacities take composite, e.g. of item "(80+)" and of item "(+10) multiplied by hours/day of required storage".

Energy storage concepts require major development effort, the outcome of which will significantly influence the future of solar options and their embedding strategies.

It is clear that the cost of energy storage will have an impact upon the utilization of solar energy in certain energy supply and demand scenarios. For example, regions with adequate pumped hydrostorage capacity, and with proximity to favorable insolation areas, offer an attractive potential for the integration of solar-electric power plants. This is so because the hydro-electric facilities, with relatively fast start-up time, provide stand-by backup for the irregularly functioning solar plants, the output of which can be advantageously directed for meeting regional demands for electric power. In this manner a "daytime only" solar power plant can successfully supplement an existing utilities energy mix network, and bring about significant savings of fossil fuels and/or energy storage capacity.

It was shown in the summation of solar energy as a resource (see Section II) that insolation values, positioning of the collectors, and proper selection of solar energy conversion system, are among the key parameters for determining the amount of energy obtainable per unit area in a given region. If we attempt a cursory optimization, we first locate a site where ≈2300 kWh(t)/m^2·a insolation and over 3000 sunshine hours/year prevail on horizontal surface (see Table 1). Considering a two-axes tracking conversion system, the solar energy input increases to about 3300 kWh(th)/m^2·a (Table 4). If the region is remote from an existing utilities network, hydrogen production can be elected to facilitate energy storage and transportation. Should this facility, for example, satisfy mid-term experimental feasibility requirements, a more suitable option would probably be in the use of the paraboloidal dish sacrificing some of the large-scale gains (as compared to heliostat field and central receiver tower), because of the high temperatures obtainable per unit effective area. Combining the selected system with a liquid hydrogen production and storage facility, a 100 MW(e) daytime operating facility could deliver about 240 million kWh(e) annually, manufacturing ≈4.4 million kg liquid hydrogen (using thermal dissociation of H_2O and liquefaction processes, consuming ≈54 kWh(e) per kg LH_2). With a conservative system efficiency and using LH_2 boil-off effectively in the process, nearly 3.8 million kg of LH_2 could be delivered annually to the energy users in a region with insufficient insolation levels. The energy in 1 kg of LH_2 is equivalent to about 39 kWh(th) [Ref. 12], which would deliver for the given sample case about 148 million kWh(th), which is equivalent to about 13 million liters of heating oil.[4] However, with the estimated capital expenditures (Tables 6 and 7) for the plant and for a LH_2 facility, a commercially viable payback time is still speculative with the current state of the art of solar-electric and hydrogen production technology. This means that significant improvements of the technology must be met featuring innovative, low-cost system designs, improved efficiencies, and long operating life.

---

[4] 13 million liters per year is equivalent to 82000 bbl per year.

If the facility should meet long-term requirements, thermal decomposition of water in central receiver tower systems may also prove economically feasible, and a significantly higher production of transportable energy may be attained. Such concepts will be evaluated in the future, as more research and development information becomes available.

The combined use of Tables 6 and 7 offers an opportunity for preliminary evaluations of various combinations of solar energy conversion systems with suitable energy storage systems. Further developments in this field are anticipated. Inasmuch as adequate literature exists on most of the conceptual and design aspects of solar systems [Ref. 3 to 13], this progress report attempts to focus on the subjects essential for conceptualizing the solar energy embedding potential.

Because the contemporary efforts in various countries are not limited to solar-thermal concepts, a comparison of characteristics with photovoltaic array concepts and their relevance to siting issues is essential (see Table 6). The possibility of a successful development of a mass production process for low-cost photovoltaic arrays [Ref. 9] stipulates a review of these potentially competitive technologies. It may require four to eight years before the feasibility of low-cost photovoltaic, fully encapsulated (weather proof) arrays may be proven (≈\$500/kW(peak)). Their system integration flexibility and equal adaptability to large-scale generation of electricity and/or hydrogen, as well as to diverse application in development of "solar buildings", postulates consideration of their long-term application.

The solar technology assessment review also revealed developments of a number of small to medium solar energy conversion systems for irrigation (pumping), process heat, electricity generation, and a multitude of other uses. The status of these efforts is subject to such rapid changes that their inclusion in regional and global consideration would be premature at this time. Nevertheless, their sizes can be estimated from the data in Table 8.

The low temperature, solar energy conversion technology represents, however, a viable contribution to future energy supply, because water and space heating energy requirements constitute a major portion of energy demands in industrialized countries, where heating oil and natural gas are used to meet such demands. To illustrate the magnitude of this issue, current estimates show that a contemporary family home (average occupancy of four persons) consumes an equivalent of 53 barrels of oil per year in the USA, while a similar home in the FRG consumes an equivalent of up to 28 barrels of oil per year, and a comparable housing unit in the industrialized part of the USSR consumes nearly an equivalent of 11 barrels of oil per year. Most of this energy is for hot water and space heating. Depending upon geographic location, insolation values, and the numerous building and heating practices in these regions, an average of about 40 to 60 per cent of the

Table 8. Basic characteristics of solar-thermal and photovoltaic power plants (in favorable insolation regions)

	Solar-Thermal-Electric	Photovoltaic
Usable Sunlight	Direct only	Total
Minimum Area (base-load)[a]	$15 m^2$/kW(e)	$32 m^2$/kW(e)
Cooling System	required	none[b]
Sun Tracking	two-axes	none[c]
System Efficiency	0.10 to 0.22	0.08 to 0.15
Maintenance	continuous (engineered)	occasional (minimal)
Access (to site)	heavy equipment (access roads)	light equipment

[a] without consideration of area utilization factor;

[b] unless high concentrators are used;

[c] at some latitudes seasonal adjustment only.

energy could be supplied by installation of solar systems (see Table 1). The estimates of attainable options (below 100°C) are summarized in Table 9. These must be viewed as a range of sample cases, because the system design trade-offs between (solar) collector area, hot water storage volume, storage tanks insulation, house insulation, and heat-pump application offer an infinite number of possibilities.

With the current cost of heating fuels the investment and amortization for these options is not attractive, but the anticipated increases of fuel cost and the future shortages of fuels should eventually yield increasing savings and a subsequently faster payback time. The energy payback time for such systems, as well as for most solar options, is below two years. Specific cases can be evaluated from the estimates in Table 10.

Recycling of metals is particularly advantageous for large-scale application of solar options, because of the reduction of energy requirements that ranges from about 78 per cent for steel to 97 per cent for aluminum. The much higher energy requirements for aluminum production stipulate

Table 9. Estimates of low temperature options in moderate insolation regions

Family House Options	Investment (System)[a]		Materials (kg)	Typical Heating Oil Savings[b] ($/year)	
	Total ($)	($/m^2)[c]			
Water heating	2500-3500	150-280	500-800	120-200	50 to 60% of Demand
Space and water heating	4000-7000	180-500	850-1000	250-350	
Space and water heating including heat-pump	8000-9000	200-630	1500-2000	400-550	60 to 80% of Demand

[a] based on industrial activities in the FRG and 1976 dollars;

[b] based on 1976 prices of heating oil in Central Europe.

[c] subject to trade-off between collectors area, water storage and building insulation.

Table 10. Energy requirements estimate for production of materials used in construction of solar options

Material	Energy Requirements (kWh(th)/t)	
	From natural resources[b]	From recycled material[b]
Iron and steel	6000 to 12000 (10000)[a]	1400 to 2000 (1700)[a]
Cooper	13000 to 36000 (30000)[a]	800 to 2000 (1500)[a]
Aluminum	60000 to 100000 (80000)[a]	1500 to 2500 (2000)[a]
Cement	2000 to 3000 (2500)[a]	-
Glass	5000 to 14000 (9000)[a]	Nearly same as from natural resources

[a] average of estimates.

[b] subject to extraction and processing effectiveness & efficiencies, as well as availability of quality raw materials.

the use of steel as the principal material, which in turn enhances the utilization of scrap without costly selection processes. This is significant in the sense that the steel industry now prefers selected (i.e. industrial) scrap to prevent contamination of processing facilities. However, when the market for a large volume of structural steel without close specifications is envisioned, the steel industry would accommodate the solar industry and process ordinary (i.e. automotive) scrap.

The energy requirements for materials production must be viewed as broad indicators, because the efficiencies of various processes and facilities vary, and if energy conservation measures are implemented, the energy requirements may be lower in the future.

In addition to the energy requirements for materials, large-scale embedding of solar options will consume substantial energy for transportation, construction, and operation of installation and maintenance equipment, spares, accommodation of labor (in cases where solar plants are constructed in remote regions), and for numerous other functions associated with such large-scale activities. Transportation energy alone is estimated at about 60 kWh(th) (equivalent)/t per 1000 km for cargo vessels; 135 kWh(th) (equivalent)/t per 1000 km for freight-train, and about 670 kWh(th) (equivalent)/t per 1000 km for diesel truck.

In terms of industrial planning, large-scale implementation of solar options may cause some "materials and capital diversion" from conventional markets (see Sections V and VI). Making conservative assumptions, based on contemporary (1976) designs, practical spacing and energy storage adjustments for collector areas, and specifying year around operation, the following approximations are useful for a cursory assessment of the "materials and capital diversion" needed in the construction of solar-thermal versions of the various options (Table 11).

The various contemporary designs applicable for the options, and the innovations that can be expected in the future, must be considered when using such estimates. Availability of optimization data depends upon the results from the experimental facilities that are in the planning stage in most industrialized nations. Certainly, lower estimates would result from the reduction of operating time and storage requirements, and if hybrid configurations were used for the production of electricity or hydrogen.

As an example, a 100 MW(e) solar-thermal plant for base-load operation in the high insolation region would require about 67500 t of structural materials, and about 225000 t of concrete. The structural materials requirement could be as low as 38000 t per 100 MW(e), if some of the innovative designs can be expected to survive the environmental deteriorations for the 30 years operating life. A next generation hybrid plant with 100 MW(e) daylight rating (no external energy storage) may require only 18000 t of structural materials and 75000 t of concrete.

Table 11. Estimates of materials and capital requirements for implementation of solar options (base-load configurations)

Insolation[b] kWh(th)/ $m^2 \cdot a$	Collector [d]		Materials[c]		Investment
	Area (m^2/kW^a)	Option	(kg/kW^a)	kWh(th)/kW	($\$/kW^a$)
2300	24	H_2	1000-1300	16000-21000	6400
	15	Electric (STEC)	600-800	9800-13000	4000
	5	Heating	100-250	2000-5000	800
1163	48	H_2	1800-2200	30000-36000	12800
	30	Electric (STEC)	1200-1600	19600-26100	8000
	10	Heating	200-500	4000-10000	1500

[a] kW(th) for heating and kW(e) for electric power and for H_2 production;

[b] global irradiation on horizontal surface;

[c] does not include concrete, the use of which varies widely from 0 to 200 kg/m^2, subject to design and site conditions.

[d] subject to trade-off considerations with energy storage capacities and insolation values (conversion efficiency of diffuse component of insolation).

Detailed consideration of large photovoltaic power plants will be due when the planned cost reduction of array (i.e. panels) will prove feasible. Until then, the information in Tables 6 and 8 is as useful as any contemporary estimate [Ref. 9].

The solar technology assessment review shows that considerable innovations in design, progress in standardization, and a better understanding of the solar energy criteria are needed for broader acceptance and favorable market penetration of the solar options. Current support of solar research and development in most of the industrialized nations promises to yield increasingly more positive approaches within a few years and, of course, increasing cost of fuels will continue to intensify the economic viability of solar options. However, an objective screening of the solar options for long-term energy mix projections cannot be performed effectively until the ultimate potential of the nuclear, coal, and other alternatives is better understood.

IV. REGIONAL STUDIES

The first regional study at IIASA on the large-scale application of solar energy options was the "Austrian Case Study" [Ref. 4, 5 & 14], where a detailed analysis of insolation values in general, and of the direct irradiation values in particular, revealed that there are potentially suitable locations even in Austria where the hybrid version of the solar-thermal power plants, consisting of heliostats field and a central tower receiver (STEC) could be attractive, if the construction cost could be held at a low enough level (i.e. below \$70/m^2 system cost of the solar-specific hardware). The delineation of construction cost is at present among the most speculative issues in considering large-scale STEC applications. Correlation analysis with known building construction cost data [Ref. 15] reveals that site preparation, foundations for the heliostats, supporting structures, and the framework for heliostat surface would cost about \$78/m^2, if constructed within 200 km from major materials and labor supply areas. This indicates that significant innovations would have to be attained to meet the desired cost limits and still manage to build such structures to last 30 years, maintain rigidity (i.e. accurate angular relationships required for aiming at the specific location of the receiver on top of the tower) and include the subsystems for two-axes tracking of sun necessary to achieve the required accuracy for concentration of solar energy.

The "Austrian Case Study" produced very illustrative graphical interrelationships of insolation data, prices of oil, cost of (hybrid version) STEC, cost of capital and attainable payback time [Ref. 5]. The concept established a useful method for concise synthesis of these key parameters, and will be pursued further as more validated inputs will become available. Better understanding is needed of the insolation values, start-up and energy storage requirements, as well as of the transitional criteria and associated energy losses during the daily solar energy inputs cycle, in order to identify the real solar energy conversion potential in the regions with less than ideal climatic conditions. In the case of Austria, the potential suitable locations appear to have an adequate annual insolation distribution (over 1150 kWh(th)/$m^2 \cdot a$, and about 2000 hours of sunshine per year) and very favorable hydrostorage capacities (pumped storage). Combined with sufficient land area and industrial capacities, the basic technical feasibility for long-term solar-thermal-electric options is promising. The uncertainties of economic estimates, however, stipulate the further need for inquiry.

The current regional solar energy study at IIASA is concerned with the ways and means for the possibilities of accelerated utilization of solar energy conversion in the Federal Republic of Germany. The study is organized into ten tasks:

(1) technological and economic state of the art:

encompassing the technological, industrial, and economic potential for large-scale development of solar options;

(2) institutional aspects:

identifying societal, legal and institutional constraints and incentives for the implementation of solar options in the FRG;

(3) prognosis for the FRG:

delineating measures and consequences of solar options integration into a future energy mix in the FRG;

(4) workshop:

organization of an experts meeting to attempt validation of the criteria affecting the acceptance of solar options;

(5) solar district heating:

evaluation of solar energy conversion limits for district heating considerations;

(6) solar-electric power technologies:

assessment of solar-thermal and photovoltaic technologies for the FRG;

(7) hydrogen production:

investigation into the hydrogen (gas and/or liquid) production potential with the use of solar energy;

(8) scenarios and options:

development of scenarios including the product of solar technology applications, and delineation of related energy supply options for the FRG;

(9) systems aspects:

synthesis of applicable solar energy systems and their interrelationships with a future FRG energy mix;

(10) aid to developing countries:

review of the FRG capacity to provide technological and industrial aid in terms of solar technology applications and associated issues and/or trading alternatives.

The study for the FRG is nearly 50 per cent completed and the results will be published in late 1977. Because of the insolation values in the region of the FRG, emphasis has been directed into the low temperature spectrum (below 100°C) of solar energy conversion, which consists primarily of water and space heating for housing and communal facilities. Preliminary assessments indicate that considerable savings of oil could be attained by an accelerated marked penetration of solar technology for the low temperature energy supply (see Table 9).

The regional studies on the large-scale embedding of solar options at IIASA are viewed as inputs for regional energy mix models, synthesizing the individual characteristics and capabilities of the regions. These models will eventually become the elements of the ultimate global energy model. The scale and the economic ramifications of this undertaking stipulate the need for an intensive validation of all the input information to prevent the development of erroneous projections. The current, formative stage of solar technology indicates some unique potentials and speculative trends, but a much more regional evaluation will be necessary before all the complex interrelationships and comparisons with other alternatives for a global energy mix are sufficiently understood.

V. SOLAR ENERGY EMBEDDING IN INDUSTRIALIZED COUNTRIES

Solar energy conversion potential in the industrialized countries should be viewed against the background of the major efforts vested in nuclear research, coal gasification, liquefaction research, and other alternatives, as well as in terms of obtainable insolation values. Large-scale embedding of solar-thermal systems will also be significantly influenced by the development of photovoltaic systems, which could offer a broader operating spectrum (converting diffuse as well as direct irradiation) and relative simplicity of installation-operation aspects. The issue is, whether the cost of such devices can really be reduced from the current $17,000 per (peak) kilowatt electric to about $500 per (peak) kilowatt before 1985, as the USA-ERDA objectives stated [Ref. 9]. In the meantime, the solar-thermal systems are within the range of technical feasibility, but subject to substantial innovations during the same time period (1977-1985).

In the low-temperature (below $100^{o}C$) energy supply, the interim use of solar options would have the potential of reducing the demand of heating oil and gas by 15 to 50 per cent before the year 2030, depending upon the incentives for increasing rates of market penetration of the solar systems. The areas in which the suitable incentives can be developed are:

(1) "solar rights" and building site layout laws;

(2) favorable building construction codes;

(3) suitable utilities regulations;

(4) standardization codes for solar hardware (assuring quality);

(5) governmental incentives (favorable tax rulings);

(6) solar hardware life cycle insurances;

(7) favorable economic measures for added value;

(8) favorable financing (loans and fiscal inducements).

The solar heating systems cost, as related to cost of conventional heating, both for water and for space, is mostly still too high and the amortization periods too long (see Table 9). Generally, in the case of family houses, the system cost is about 10 to 15 per cent of the building construction cost. Future increases of fuel cost and future effectiveness of collectors will improve the economic viability of the solar options. If savings of 1000 to 4000 liters heating oil per year and family house of the various configurations (in central European or USA climate) is related to the associated investment, ranging from $2500 to $9000 per house installation, a saving of one million barrels of heating oil[5] per year would require, for example, installation of solar collectors of a medium system without heat-pump

---

[5] crude oil yields about 30 per cent of its volume (≈48 liters/bbl) as heating oil, subject to refinery operations.

on 155000 to 310000 family houses, depending upon the systems used. This means an average of about 1.5 million to 3.0 million m^2 of collector area (1.5 to 3.0 km^2) manufactured, and about 775 million to 1.0 billion invested by the homeowners (1976 dollars). This would be the case in a climate with nearly 1100 kWh(th)/$m^2 \cdot a$ total insolation value, where 1.0 m^2 of effective collector area is equivalent to an annual saving of about 50 to 60 liters of heating oil (or over 100 liters when oil heating operating full year is integrated in the estimates).

In an industrialized country such as the FRG, the current heating oil market is approaching nearly 380 million barrels per year. To reach, for example, 15 per cent savings (57 million bbl) before the year 2000 represents the following approximate diversion of materials and capital:

57 million bbl = 9.06 billion liters heating oil/year ;

$\approx$ 165 million m^2 collector area
(or 165 km^2) ;

$\approx$ 5.5 million family houses ;

$\approx$ 5.0 million t of materials ;

$\approx$ \$30 billion capital investment
(1976 dollars).

Distributed over a 20-year period, this means an energy investment of over 90 billion kWh(th), or over 90TWh(th), which is certainly within the capacity of the FRG. This does mean, however, that most new family houses constructed for oil heating in the 20-year period, and a considerable number of existing houses would have to be equipped with solar systems. The complexity of impacts of such an alternative on the economic and social structure of FRG is yet to be determined.

In the high temperature area of solar energy conversion and electricity and/or hydrogen production, the embedding of solar options is equally difficult to evaluate. The industrialized countries have now about 28 per cent of the world population, using nearly 82 per cent of the primary energy produced in the world. The gross national product (GNP), employment, and energy consumption of the industrialized countries are maintaining reasonably close relationship, and electricity is considered the most economically efficient form of energy. Thus, the generation of electricity with solar options is desirable within the framework of a future energy mix, if it can be economically compatible with the other forms of energy available. The current global trend in consumption of electric energy is nearly one of exponential growth. If, for example, 70 GW(e) should be supplied by solar-thermal plants before the year 2000, using the 100 MW(e) base-load units, then 700 of the STEC defined in Table 11 and placed in high insolation regions (at about 2300 kWh(th)/$m^2 \cdot a$) would have to be constructed. The parameters based on the composite of a contemporary, first generation STEC design would indicate:

1 GW(e) ≈ ten STEC,each producing 100 MW(e) base-load;

≈ 675000 t of structural materials, and about 2.25 million t of concrete;

≈ $4.0 billion capital investment.

All of this is subject to the screening procedures adjustment (see Section III) and adjustment of the parameters applicable for each specific site location. The land area required for such ten STEC units would range between 39 to 50 km^2, depending upon climate and the topographic features. For the stated example of 700 of STEC units, all the preceding cursory estimates must be multiplied by 70, which shows the following materials and capital diversion requirements:

70 GW(e) ≈ 700 STEC, each producing 100 MW(e) base-load;

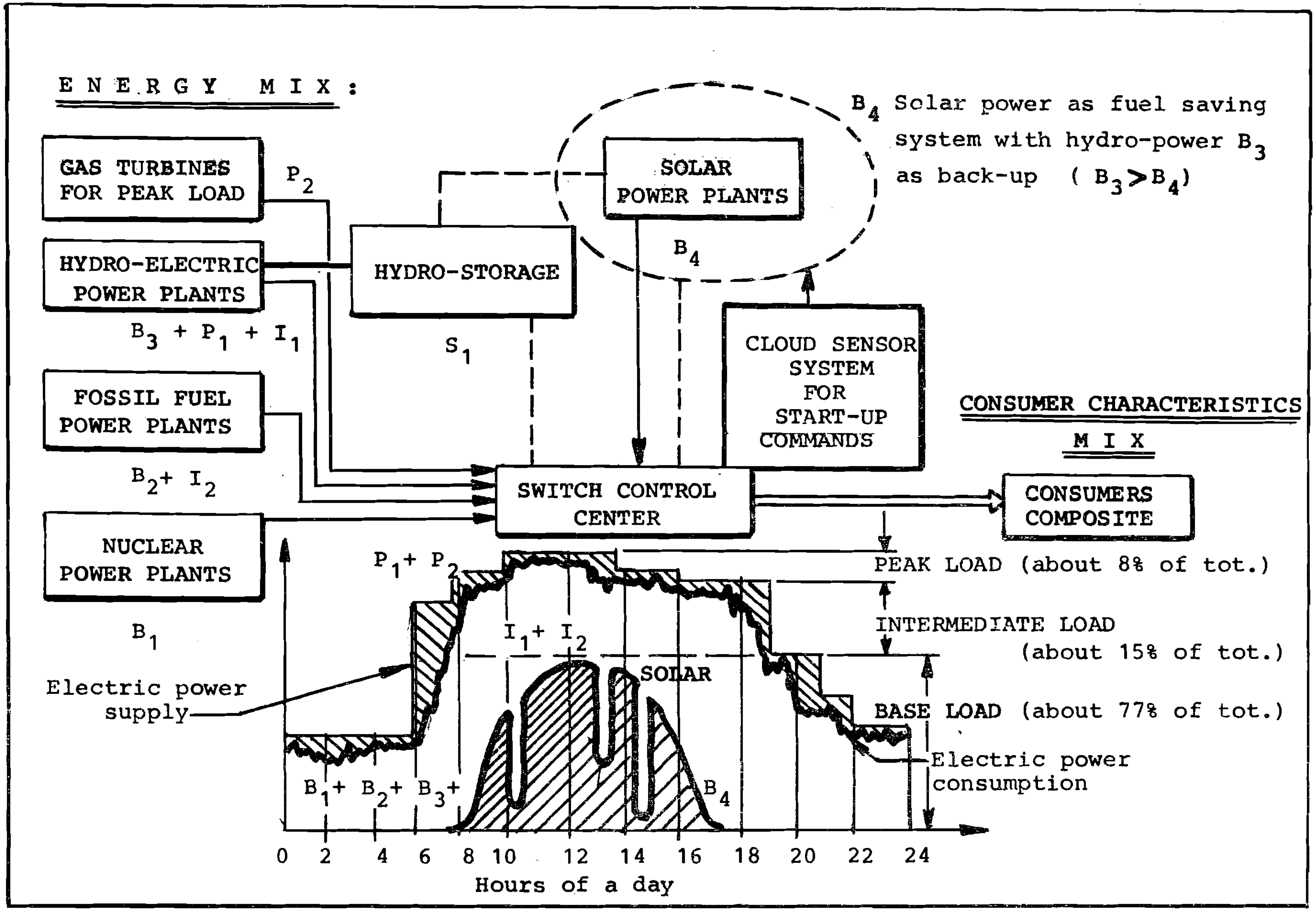
≈ 47.25 million t of structural materials, and about 158 million t of concrete;

≈ about $280 billion capital investment.

The commitment of those resources in 20 years for such an undertaking is certainly not viewed as probable at this time, until the results of the effort vested in nuclear, coal, and other alternatives are identifiable. The research and development progress envisioned for the next 20 years will undoubtedly yield distinctly more innovative solutions for the solar options.

The issue of integrating solar-electric plants into existing utilities network has also been considered during the study. As long as the hybrid versions are chosen--which are economically more desirable for the interim, prototype operations--the solar power plants would be a part of the energy mix (Figure 1), subject to limitations of the stand-by power capacity. It is envisioned, as in Figure 1, that each solar power plant would be surrounded by a cloud sensor system which would feed data into the switch-control center. As long as the stand-by capacity and rapid on-line capability (hydro-electric and gas-turbine facilities) is adequate to substitute for solar power plant output when needed, the integration would not pose special problems. Beyond that, additional stand-by capacity would have to be provided to maintain an adequate margin of power supply. This would, of course, increase the capital investment requirements.

Figure 1. Integration of solar energy conversion powerplant into utilities network



The currently identifiable strategy for the development of STEC embedding potential points to the need to construct prototype STEC in each climatically and topographically characteristic location to learn about the operating criteria of these power plants. Conservative construction of these facilities would provide for acceptable payback, regardless of future structuring of the energy mix.

VI. SOLAR ENERGY EMBEDDING IN DEVELOPING COUNTRIES

The developing countries have now about 72 per cent of world population, using nearly 18 per cent of the primary energy produced in the world. In addition, there is a growing trend of population migration from rural to urban areas of these countries. This places additional burden on energy production, because the per capita energy consumption in urban regions is much higher than that in rural regions. United Nations data indicate that in the year 2000, about 51 per cent of the world population ($\approx$ 3.0 billion) will be in urban areas, and 49 per cent ($\approx$ 2.9 billion) in rural areas. Reducing these estimates to the developing countries, about 2.16 billion will live in the urban areas of the developing countries. Realizing that increase of gross domestic products per capita is a prerequisite for growth of energy availability, and that a reasonable goal would be to provide at least the urban population with adequate supply of electric power, at least one kW(e) per capita should be produced within a generation. This amounts to 2.16 TW(e).

Again stipulating, to start with, only 10 per cent of that for STEC application before the year 2000, the requirement would be for 21600 STEC power plants with 100 MW(e) baseload capacity each. This number of capital intensive STEC units with the current state of the art represents estimates about $8.64 trillion (not including transportation of the hardware to the sites!), which makes further considerations academic. Developing countries that may choose to select STEC concepts for daylight operation only can defer the complexities and cost of energy storage and simply schedule the electric power-consuming activities to coincide with effective sunshine hours.

Some thoughts were given to compensation trade development, which is certainly among the most viable means for financing the capital intensive solar options. But, with the exception of OPEC countries, such approach has shown a range of complexities, the analysis of which is beyond the resources of this task.

It is obvious, therefore, that much more extensive studies and availability of validated information on the next generation of solar technology will have to be satisfied before serious considerations of solar energy for global supply of electric power can continue. Even a 50 per cent reduction of the contemporary capital diversion from other planned tasks would not provide basis for serious feasibility considerations of the STEC options in the developing countries. Many of these countries have, of course, hydroelectric power and other more viable options. This does not, however, invalidate the usefulness of gradually applying solar energy conversion for smaller functions in remote areas, where the supply of conventional fuels would be too expensive.

The use of solar systems for irrigation (pumping), the supply of processing heat (agricultural drying processes), small and medium size power supplies ($\approx$10 to 100 kW(e)) and numerous other applications will be attractive for some remote regions. Such systems do not, however, contribute significant energy growth in global terms. Eventually, the development of "solar breeders", i.e. modular STEC that is gradually increasing its size by revenues for its outputs, may also prove attractive for some regions. Only a detailed evaluation of resources and energy alternatives for each region can provide a more accurate delineation of the solar options potential in the developing countries.

The second report to The Club of Rome [Ref. 16 and 17] divided the world into ten regions. Cursory evaluation of their capital availability, steel production, and transportation capacities revealed that an orderly rate of STEC manufacturing and export to the developing countries (supported by compensation trading), would probably provide 500 STEC units of 100 MW(e) rating each by the year 2030, assuming that reasonable design optimization was achieved. This would approximate 50 GW(e) or about 23 W per capita in the urban regions of the developing countries. To bring this share to 1 kW(e)/capita by the year 2030 would obviously require international cooperation and diversion of capital, materials, and skilled manpower on a scale for which there is no precedence.

VII. CONCLUSIONS AND RECOMMENDATIONS

The current state of the art of technology for large-scale deployment of solar options is still in its formative stage, which makes long-term projections on regional and global scales much too speculative. Nevertheless, even the most optimistic interpretations of insolation values and potential improvements in conversion efficiencies do not change the fact that most solar options are capital intensive. However, neither the area requirements nor the material requirements seem to be long-term constraints. The long operational integrity requirements needed to achieve acceptable payback periods are among the problems future innovations must solve.

The evaluation of the low temperature solar options indicates promising potential, subject to quality improvement of the hardware and decrease of cost. Contemporary technology shows capital requirements of about $2500 to $3500 for water heating units in family houses, and about $4000 to $9000 for space and water heating units in family houses. Favorable amortization of such systems depends upon future increases of fuel cost for conventional heating.

The large-scale embedding of solar options in the industrialized countries should be viewed in perspective with the vested efforts in nuclear, coal and other alternative research and developments. Most of these efforts are also not far enough to reliably compare their relative merits. It may require a decade before the long-term energy mix can be seriously evaluated. During that time, solar technology may gain from a better understanding of solar energy inputs, the development of more efficient, cost-effective energy collection and storage methods, superior, low-cost heat transfer fluids, low-cost photovoltaic arrays, and many other innovations. The current inhibitions for large-scale implementation of most solar options, caused by their capital-intensive nature, will be improved by increasing cost and decreasing availability of conventional fuels.

This assessment used realistic solar energy conversion efficiencies, but somewhat speculative materials demand estimates, based on the composite of contemporary information. The significant effects of hardware, equipment and personnel transportation to sites, their topographic features and soil mechanism make a realistic evaluation of materials and equipment demands subject to many special considerations, which are beyond the scope of this study. The uncertainties of insolation values and the attainability of maintenance-free, long operating life of the solar systems cannot be assessed until the presently planned prototype facilities will provide some realistic data. For example, the cost and performance estimates of the STEC concepts vary a great deal even in their hybrid versions ($\approx$ $600 to $1400/kW(e) in favorable insolation regions), and even more in their base-load versions, which are over three times more capital-intensive ($\approx$ $4000 to $5300/kW(e) in same regions), because of the heat energy storage capacities necessary to facilitate base-load operating durations comparable with conventional power plants (i.e. plant load factor of at least 68% on-line capacities). Average material requirements for most solar options are approximately 45 kg/m^2 of collector area, when using steel as principal material.

A large-scale embedding of solar options in the developing countries during the next 30 to 50 years depends upon the international development of compensation trading and a large-scale diversion of capital, materials, and skilled manpower in the industrialized countries, for which there is no precedence. Whether a gradual use of the "soft" technology will precede serious application of solar options (i.e. for electricity production and industrialization) will probably depend upon the progress of solar technology in the industrialized countries, and upon international cooperation.

The performance limitations of solar options in marginal insolation regions suggest serious consideration of concentrating on regions with favorable insolation values and transporting the energy to the marginal regions. This does, unfortunately, alter the idea of fuel imports independent energy systems and associated economic and political ramifications.

The need to screen increasing volumes of solar technology information, and the desirability to clarify the often misleading claims about the real potential of solar energy strongly suggests an increasing emphasis on data validation. Here is a unique opportunity for the IIASA Energy Program to systematically pursue delineation of solar energy options with identification of realistic, economic, social, and regional criteria. The resources requirements for such task would, however, be a multiple of the resources available for this study, because of the time-consuming difficulties in acquiring realistic information.

ACKNOWLEDGMENT

The first IIASA solar energy task progress report for 1975/76 was prepared to provide an interim overview of the principal criteria of solar options. Considerable inspiration in many key areas was obtained in discussions with W. Häfele, F. Jäger, D. Meadows, W. Sassin, B. Schmidt-Küntzel, N. Weyss, J. Weingart, W. Korzen and many others whose interest and comments are truly appreciated.

References

[1] Budiko, M.I., *Atlas of Earth's Thermal Balance Charts*, Moscow, USSR, 1963.

[2] Löf, G.O.G., et al., *World Distribution of Solar Radiation*, The University of Wisconsin, Solar Energy Laboratory, 1966.

[3] Backus, C., *Terrestrial Photovoltaic Power Systems With Sunlight Concentration*, NSF-RA-74-076, Arizona State University, and Spectrolab (Division of Textron), Tuscon, Ar., 1974.

[4] Weyss, N., *Fallstudie Solarstrom in Österreich (Gewinnungsmöglichkeiten von Solarstrom in Österreich)*, Studienauftrag des Bundesministeriums für Wissenschaft und Forschung, Vienna, Austria, manuscript, April 1977.

[5] Häfele, W. et al., *Second Status Report of the IIASA Project on Energy Systems, 1975*, RR-76-1, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

[6] *Solar Thermal Conversion Mission Analysis*, ATR-74(7427-16)-2, I-VI, Aerospace Corporation, El Segundo, Ca., 1975.

[7] Caputo, R. et al., *Program Review Comparative Assessment of Orbital and Terrestrial Central Power Stations*, Jet Propulsion Laboratory, Pasadena, Ca., 1975.

[8] Caputo, R. et al., *Quarterly Review Comparative Assessment of Orbital and Terrestrial Central Power System/ July-August-September 1975*, Jet Propulsion Laboratory, Pasadena, Ca., 1975.

[9] Bell, C.R., *Assessment of a Solar Photovoltaic Power Conversion System for Central Station Application*, 900-702, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Ca., 1975.

[10] *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, MTR-6970, The Mitre Corporation, McLean, Va., 1975.

[11] Eldrige, F.R., *Wind Machines*, MTR-6971, The Mitre Corporation, McLean, Va., 1975.

[12] Bockris, J.O'M., *Energy, The Solar-Hydrogen Alternative*, The Architectural Press, London, 1976.

[13] Häfele, W. and W. Sassin, *Applications of Nuclear Power Other Than for Electricity Generation*, RR-75-40, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

[14] Weyss, N., Nutzung der Sonnenergie, insbesondere in Kraftwerken, *Zement und Beton*, 4, Vienna, Austria, 1976.

[15] *Building Construction Cost Data 1975*, Robert Snow Means Co., Inc., Duxbury, Mass, 1974.

[16] Meadows, D. et al., *The Limits to Growth*, Universe Books for Potomac Associates, New York, 1972.

[17] Mesarovic, M. and E. Pestel, *Mankind at the Turning Point*, E.P. Dutton & Co., Inc., New York, 1974.

CONVERSION FACTORS[d]

1 million tons[a] SKE[b] = 8.14 TWh(th) = (2.93TWh(e))[c]
= 678 thousand t oil

1 t SKE = 8140 kWh(th) = (≈2930 kWh(e))[c]
= 4.79 bbl
= 7 million kcal

1 t crude oil = 12000 kWh(th) = (≈4320 kWh(e))[c]
= 7.0 bbl
= 10.32 million kcal

1 bbl oil = 1700 kWh(th) = (≈612 kWh(e))[c]
= 159 liters oil
= 1.46 million kcal

1 kWh(th) = 860 kcal = 3600 kJ = 1.34 HPh
= 0.123 kg SKE
= 3412 Btu

---

[a] metric tons;

[b] SKE = Steinkohleeinheit = equivalent coal unit;

[c] with conversion efficiency of 36 per cent.

[d] because of various SKE conversion values and varied system efficiencies, these factors ought to be viewed only as guideline for the comparisons in text.