Earth Benefits of Solar Power Satellites

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ABSTRACT

The potential of solar energy to meet global needs is surveyed with emphasis on solar energy conversion in space for use on Earth. The advantages of this approach are compared with terrestrial solar energy conversion methods. The concept of the solar power satellite (SPS) is presented and the technology options for converting solar energy in space, transmitting power, and converting it on Earth into electricity are summarized. The requirements for space transportation systems, orbital assembly, and maintenance are reviewed. Economic and institutional issues are outlined and the environmental impacts of SPS operations are highlighted. A phased SPS development program is presented and possible organizational structures to achieve the potential of this major option for power generation on Earth are outlined.

1. INTRODUCTION

We are not masters of our destiny, and yet, the actions we take now will determine it. Our perception of the future has changed radically, as we have gained a new perspective of the limits to the availability of energy resources so dramatically brought to our attention in 1973. Intuitively, in the 60’s, we still perceived the world as infinite, a perception which previously had permitted us to act almost without constraint. In the early 70’s, we became conscious that this view was inappropriate. As a result, we are more uncertain about the future, and our general expectation and optimism have decreased. We have seen national economies seriously dislocated by sharply increased energy costs. The resulting energy problem has brought a consciousness to the broader public of what actually has been a reality for a long time, that energy is the key to the social development of man and necessary to improving the quality of life beyond the basic activities necessary for survival.

The recognition that no one energy source will, by itself, meet all future energy demands, that the search for new sources of non-renewable fuels can only put off the day of their ultimate exhaustion, and that uncertainties in achieving the global potential of known energy conversion methods are great has led to renewed emphasis on the inexhaustible energy source represented by the sun.

Solar energy could provide for virtually unlimited amounts of energy to meet all conceivable future needs. Yet, today we are using practically no solar energy. Instead, we are burning cheap oil and gas and cheap oil and gas are limited resources. In principle, we have infinite energy in a finite world; whereas, in reality, we are using finite energy in a world that was, until recently, perceived to be infinite. Obviously, we cannot easily switch from the way we use our energy resources now to a future where we will use renewable resources.

Numerous studies project what will happen in the next 15 years and how we can deal with our energy problem. Mostly, these studies focus on pricing, management, and allocation of available resources that must be dealt with within an existing infrastructure.

However, changes which could be made within the existing infrastructure would have an impact only after 15 years or more. But, they will have to be made to bring about the transition from cheap oil and gas and other non-renewable energy resources to the renewable energy sources which will be essential to the proper functioning of the energy economies in the future. Therefore, our time horizon must encompass a period of up to 50 years, because the conceivable impacts of renewable energy sources on society and the environment will not be visible until after that. Shifting too soon or too quickly to solar energy could strain national economies. Shifting too late or too slowly might also impose insurable pressures on some fossil fuels, resulting in sharply escalating prices and consequent damage to these economies, as has already been experienced during 1973 and is continuing to be felt now. Huge energy supplies will have to become available if the developing countries are to approach the economic level of industrialized countries (Table 1). The future energy resource requirements of developing countries will be more than four times the total world energy production of 1970. As industrial countries will remain major users of the world’s energy resources, the prospect of supplying the equivalent of 30 billion metric tons of coal per year to meet the aspirations of developing countries and the resulting global environmental effects, demonstrate that solar energy would have to play an increasingly important role.

2. THE POTENTIAL OF SOLAR ENERGY

The potential of solar energy as a source of power has been recognized and evaluated for more than 100 years. Each square meter of Earth’s surface exposed to sunlight at noon receives the equivalent of one kilowatt, or a total potential power input 100,000 times larger than the power produced in all the world’s electrical generating plants together. Efforts to harness solar energy, which had accelerated during the last year.
TABLE 1

COMPARISON OF UNITED STATES WITH ALL OTHER USERS OF WORLD ENERGY RESOURCES
(per capita — in metric tons of coal equivalents, 1970)

<table>
<thead>
<tr>
<th>Region</th>
<th>Population</th>
<th>Energy</th>
<th>Per Capita Consumption</th>
<th>Actual Deficit</th>
<th>U.S. Equivalent Energy Use</th>
<th>Gap (minus U.S. level)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Production</td>
<td>Consumption</td>
<td>Production/ Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. United States</td>
<td>205</td>
<td>2,054</td>
<td>2,282</td>
<td>11.1</td>
<td>-228</td>
<td>31,868</td>
</tr>
<tr>
<td>2. Soviet Union</td>
<td>243</td>
<td>1,213</td>
<td>1,079</td>
<td>4.4</td>
<td>+</td>
<td>8,436</td>
</tr>
<tr>
<td>3. EEC (9)</td>
<td>284</td>
<td>514</td>
<td>1,228</td>
<td>4.3</td>
<td>-714</td>
<td>1,154</td>
</tr>
<tr>
<td>4. Japan</td>
<td>104</td>
<td>55</td>
<td>332</td>
<td>3.2</td>
<td>-277</td>
<td>-8,010</td>
</tr>
<tr>
<td>China</td>
<td>760</td>
<td>420</td>
<td>426</td>
<td>.5</td>
<td>+</td>
<td>-34,305</td>
</tr>
<tr>
<td>World</td>
<td>3,707</td>
<td>7,000</td>
<td>6,843</td>
<td>1.8</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>World (minus 4 regions listed above)</td>
<td>2,871</td>
<td>3,164</td>
<td>1,922</td>
<td>.7</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

1. Totals in 10^6 metric tons of coal equivalents.
2. Not applicable.

Source: Reference 1.

half of the 19th and the beginning of the 20th century as industrialization increased the global energy needs, subsided with the successful development of energy economies based on the use of oil and gas. Not until the early 1970’s did the development of solar energy technology to produce power — by concentrating solar radiation to generate high temperatures to power heat engines, by direct conversion of solar radiation with photovoltaic processes, by photochemical conversion to produce fuels and by indirect methods such as biomass conversion based on the use of products of photosynthesis, wind energy conversion and ocean thermal energy conversion — again begin to be seriously pursued.

But these developments are being pursued regionally without — at least so far — consideration of the new, even unique role that solar energy can play as a global energy resource in the future. At times, this role has been repudiated by emphatic dismissal or ridicule or through uninformed underestimates of its global potential. The degree to which solar energy technology will be successfully applied will largely depend on its economics, which, in turn, will depend on the reduced availability of non-renewable fuels and their future costs.

Still, the successful and widespread introduction of solar energy technology will require considerable development to strike the appropriate balance among the conflicting requirements of economics, the environment, and society’s needs. The political consequences of increasing solar energy use are likely to be the most far reaching and may require extensive and unprecedented international cooperation, which could lead to a safer and more stable world than would the use of other energy resources based on non-renewable fuels, especially since most of the latter are under the political control of only a few nations.

The major challenge to the application of solar energy on a global scale is the fact that it is a distributed resource with a low supply density which must serve societies with a high demand density. In the past, population densities were limited by the amount of food that could be produced on a given area of land. However today, mechanization of agriculture and resulting rural underemployment has led to the movement of people to distant cities where they seek an elusive existence.

The potential of distributed solar technology would appear to be sufficient to meet the energy demands of rural populations. However, urban populations would have great difficulty in meeting their demands with this technology, even if urban centers were located in areas with exceptionally favorable supply densities from renewable resources. In the coming decades, the global population will be less likely to live in villages and single homes. Thus, it would be very optimistic to expect that distributed solar technologies would be able to meet even a low global energy demand unless societies were willing to change their life styles on an unprecedented scale. It is unrealistic to assume that modern societies would deliberately change their life styles to meet changing conditions unless forced to do so. The various solar technologies should be developed so that they are most appropriate to meet social and economic criteria with acceptable environmental impacts and be of the greatest overall benefit to society.
One of these criteria pertains to the material requirements for construction and maintenance of solar systems. Solar systems are the most capital intensive because of the low flux density of solar energy compared to other energy forms. Furthermore, these systems must operate in a variety of natural environments and must have sufficient structural stability to ensure operation and survival under occasional extreme conditions of wind, rain, snow and earthquakes as well as continuous routine environmental conditions such as dust deposition, corrosion, seasonal temperature extremes and the effects of solar radiation. The requirement to withstand these environmental effects translates into a minimum mass density of at least 10 kg/m$^2$, indicating that unless advanced and lightweight solar systems with extended lifetimes can be developed, enormous amounts of commodity materials would be required for the construction and maintenance of solar systems on a global scale. The challenge, therefore, is to develop solar system designs which are very low in mass and possess an extremely long lifetime. These considerations point to the advantages which can be gained in constructing a solar system in space, where the absence of gravity and environmental effects could significantly reduce the material requirements and achieve the desirable long-life characteristics for the solar energy conversion system.

3. THE SOLAR POWER SATELLITE CONCEPT

In view of these considerations of the potential of solar energy to meet global requirements, solar energy conversion methods which can meet the demands of modern societies for the continuous supply of power will need to be developed. Such methods will have a significant global impact, be conserving of materials resources, be economically competitive with power generation methods based on the use of non-renewable energy sources, be environmentally benign, and be acceptable to the nations of the world.

One of the major options for meeting this goal is embodied in the solar power satellite (SPS) concept.

It is widely acknowledged that man's conquest of space had a most profound influence on technological advances. It demonstrated that evolutionary progress need not be confined to the Earth's surface. For example, satellites for Earth observation and for communications already significantly affect the lives of the Earth's population — and the indications are that there is no limit to the uses of space technology for the benefit of society. Therefore, a logical extension of the efforts to harness the Sun was to use space technology to overcome terrestrial obstacles, such as inclement weather and the diurnal cycle, for the large-scale conversion and application of solar energy. If satellites could be used for communications and for Earth observations, then it was also logical to develop satellites that could convert solar energy and place them in Earth orbits, particularly geosynchronous orbits (GEO), where they could generate power continuously during most of the year. With their year-round conversion capability, such satellites could overcome some of the major obstacles to large-scale installation on Earth, i.e., the huge conversion area requirements and means for energy storage. Thus the demonstrated capability of industrialized society to develop high technology could be applied to the development of solar energy conversion methods in space on a scale which may not be possible on Earth.

In the 1960's, the logical soundness of using the synergism of solar energy conversion technology and space technology led to the concept of the SPS. As conceived, the SPS would convert solar energy into electricity and feed it to microwave generators forming part of a planar, phased-array transmitting antenna. The antenna would precisely direct a microwave beam of very low power to one or more receiving antennas at desired locations on Earth. At the receiving antennas, the microwave energy would be safely and efficiently converted to electricity and then transmitted to users. An SPS system would comprise a number of satellites in GEO, each beaming power to one or more receiving antennas.

Among the primary arguments for solar energy conversion in space for use on Earth is the nearly constant availability of solar radiation in GEO as compared with solar radiation received on Earth. Furthermore, solar energy available in GEO will be at least four times the solar energy available even in favorable locations on Earth because of interruptions caused by weather and night. This also implies that terrestrial photovoltaic power systems are more likely to be useful as a displacement of electric utility capacity, e.g., gas turbines, because such photovoltaic systems could be operated intermittently with appropriate utility provided system storage to meet peak load demands rather than be called upon to generate baseload power which would require substantial reserve capacity in the utility system. By contrast the SPS will be capable of generating baseload power with either none or very limited utility provided system storage.

In recognition of the potential of the SPS as a large-scale global method of supplying power to the Earth, the challenges posed by the SPS concept are being explored through feasibility studies of the technical, economic, environmental, social and international issues by the U.S. Department of Energy and NASA. The status of the SPS development to date has been reviewed and the issues which require resolution highlighted in a position paper issued by the American Institute of Aeronautics and Astronautics.

As originally conceived, an SPS can utilize current approaches to solar energy conversion, e.g., photovoltaic and thermal-electric, and others likely to be developed in the future. Among these conversion processes, photovoltaic conversion represents a useful starting point because solar cells are already in wide use in satellites. An added incentive is the substantial progress being made in the development of low-cost, reliable photovoltaic systems and the increasing confidence in the capabilities of achieving the required production volumes. Because the photovoltaic process is pas-
sive, it could reduce maintenance requirements and achieve at least a 30-year or even several hundred years operating lifetime for an SPS. Micrometeoroid impacts are projected to degrade 1% of the solar cell array area over a 30-year exposure period. Because of the lesser probability of impact larger meteoroids are less likely to affect the solar cell array.

Several photovoltaic energy conversion configurations applicable to the SPS concept are being considered (Figures 1a and 1b). For these configurations, silicon, and gallium arsenide solar cells with and without concentrators could be used.

For use in the SPS the solar cells will have to be highly efficient, of low mass per unit area, and radiation-resistant during transit to and in operation in GEO. They will have to be producible at rates and in volumes consistent with an SPS deployment schedule. To extend the lifetime of the solar cells, annealing methods could be utilized to eliminate or reduce the degrading effects of accumulated radiation exposure.

Of interest for the SPS is the use of gallium arsenide for solar cells because at elevated temperatures their efficiency does not degrade as fast as that of the lower-band-gap semiconductors; therefore, they can be used in systems utilizing concentrated solar energy. In addition, gallium arsenide solar cells are more resistant than silicon cells to radiation damage, thus promising a longer life as well as higher performance in the space environment.

The mass of the solar cell arrays (Table 2) is the dominant component for both of the photovoltaic SPS designs. The scale of commitment of capital, material and labor to construct large-scale manufacturing facilities and to produce the solar cell arrays for the SPS (Table 3) would have to be exceeded by several factors if an equivalent baseload power output were to be generated with photovoltaic energy conversion devices located on Earth.

Gallium arsenide solar cells emerge as the most favorable but when one compares the efficiency of several SPS design configurations (Figure 2), silicon solar cells are favored for near-term demonstration tests.

4. TECHNOLOGY OPTIONS FOR POWER TRANSMISSION TO EARTH

To transmit the power generated in the SPS to Earth, there are two optional transmitting methods:

- a microwave beam, or
- a laser beam.

4.1 Microwave Power Transmission System

Free-space transmission of power by microwaves is not a new technology. In recent years, it has advanced rapidly and system efficiencies of 55%, including the interconversion between dc power and microwave power at both terminals of the system, are being obtained. The application of new technology is projected to raise this efficiency to almost 70%.

4.1.1 Microwave Power Generation

The devices which are being considered for converting dc voltage to rf power at microwave frequencies in the SPS are crossfield amplifiers (Amplitrons) and linear beam devices (Klystrons). The Amplitron uses a cold platinum metal cathode operating on the principle of secondary emission to
TABLE 2
5-GW SPS SUBSYSTEM MASS COMPARISON FOR SI AND GaAlAs SOLAR ARRAYS
MASS-$10^6$ kg

<table>
<thead>
<tr>
<th>Solar Array</th>
<th>GaAlAs, CR=2</th>
<th>Si, CR=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Structure</td>
<td>4.172</td>
<td>3.388</td>
</tr>
<tr>
<td>Secondary Structure</td>
<td>0.581</td>
<td>0.486</td>
</tr>
<tr>
<td>Solar Blankets</td>
<td>6.998</td>
<td>22.051</td>
</tr>
<tr>
<td>Concentrators</td>
<td>0.966</td>
<td></td>
</tr>
<tr>
<td>Power Distribution &amp; Cond.</td>
<td>1.144</td>
<td>1.134</td>
</tr>
<tr>
<td>Information Mgmt. &amp; Control</td>
<td>0.050</td>
<td>0.050</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>Antennas</td>
<td>13.362</td>
<td>13.362</td>
</tr>
<tr>
<td>Primary Structure</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td>Secondary Structure</td>
<td>0.798</td>
<td>0.788</td>
</tr>
<tr>
<td>Transmitter Subarrays</td>
<td>7.178</td>
<td>7.178</td>
</tr>
<tr>
<td>Power Distribution &amp; Cond.</td>
<td>2.189</td>
<td>2.189</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>2.222</td>
<td>2.222</td>
</tr>
<tr>
<td>Information Mgmt. &amp; Control</td>
<td>0.830</td>
<td>0.830</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>0.126</td>
<td>0.126</td>
</tr>
<tr>
<td>Array-Antenna Interfaces</td>
<td>0.147</td>
<td>0.147</td>
</tr>
<tr>
<td>Primary Structure</td>
<td>0.094</td>
<td>0.094</td>
</tr>
<tr>
<td>Secondary Structure</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Mechanisms</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td>Power Distribution</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Subtotal</td>
<td>27.327</td>
<td>40.787</td>
</tr>
<tr>
<td>Contingency (25%)</td>
<td>8.832</td>
<td>10.197</td>
</tr>
<tr>
<td>Total</td>
<td>34.159</td>
<td>50.984</td>
</tr>
</tbody>
</table>

Note: CR = Concentration Ratio
Source: References 8 and 9.

TABLE 3
SOLAR ARRAY PRODUCTION REQUIREMENTS*

<table>
<thead>
<tr>
<th>Material</th>
<th>Concentration Ratio</th>
<th>Total Array Area (km²)</th>
<th>Production Rate¹ (m²/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 SPS/year</td>
</tr>
<tr>
<td>Silicon</td>
<td>1</td>
<td>110.2</td>
<td>12,600</td>
</tr>
<tr>
<td>Gallium Arsenide</td>
<td>2</td>
<td>61.2</td>
<td>6,990</td>
</tr>
</tbody>
</table>

*Note: 10-GW at Utility Interface.
One Si SPS (CR=1) with 110.2 km² of Array.
Two GaAs SPS's (CR=2), with 30.6 km² of Array each.

1. Assuming 100% yield, 24 hours/day, 365 days/year.

Source: Reference 7.

achieve a nearly infinite cathode life. With an output of 5 kW it could operate at an efficiency of 90%. The Klystron could operate at an efficiency of 80% with an output of 70 kW but will require a more complex cooling system. Microwave solid-state power transistors are also under consideration.

Considerations of mass, costs, and efficiency at specific frequencies have led to the selection of a frequency within the industrial microwave band of 2.40 to 2.50 GHz.

4.1.2 Microwave Beam Transmission

The transmitting antenna is designed as a circular, planar, active phased array having a diameter of about one kilometer. Microwave power can be transferred at high efficiency
when the transmitting antenna is illuminated with an amplitude distribution which is of the form \((1-r^2)^n\) and when the phase front of the beam is carefully controlled at the launch point to minimize scattering losses.\(^{11,12}\)

Space is an ideal medium for the transmission of microwaves; a transmission efficiency of 99.6% is projected after the beam has been launched at the transmitting antenna and before it passes through the upper atmosphere. To achieve the desired high efficiency for the transmission system while minimizing the cost, the geometric relationships between the transmitting and receiving antennas\(^{12}\) indicate that the transmitting antenna should be about one kilometer in diameter, while the receiving antenna should be about ten kilometers in diameter.

The power density at the receiving antenna will be a maximum at the middle and will decrease with distance from the center of the receiver. The exact size of the receiving antenna will be determined by the radius at which the collection and rectification of the power becomes marginally economical.

The transmitting antenna is divided into a large number of subarrays. A closed-loop, retrodirective-array phase-front control is used with these subarrays to achieve the desired high efficiency, pointing accuracy, and safety essential for the microwave beam operation.\(^{13}\) In the retrodirective-array design, a reference beam is launched from the center of the receiving antenna and is received at a phase comparator at the center of each subarray and also at the reference subarray in the transmitting antenna center.

4.1.3 Microwave Power Reception and Rectification

The receiving antenna is designed to intercept, collect, and rectify the microwave beam into a dc output with high efficiency.\(^{12,13}\) The dc output can be designed to either interface with high-voltage dc transmission networks or be converted into 60-Hz alternating current. The receiving antenna consists of an array of elements which absorb and rectify the incident microwave beam. Each element consists of a half-wave dipole, an integral low-pass filter, diode rectifier and bypass capacitor. The dipoles are de-insulated from the ground plane and appear as rf absorbers to the incoming microwaves.

The collection efficiency of the array is relatively insensitive to substantial changes in the direction of the incoming beam. Furthermore, the efficiency is independent of potentially substantial spatial variations in phase and power density of the incoming beam that could be caused by non-uniform atmospheric conditions.

The amount of microwave power received in local regions of the receiving antenna can be matched to the power-handling capability of the microwave rectifiers. The rectifiers, which are Schottky barrier diodes made from gallium arsenide material, have a power-handling capability several times that required in the SPS application. Any heat resulting from inefficient rectification in the diode and its circuit can be convected by the receiving antenna to ambient air, producing atmospheric heating which will be only twice that of urban areas; because only 15% of the incoming microwave radiation would be lost as waste heat. The low thermal pollution entailed in this process of rectifying incoming microwave power cannot be equaled by any known thermodynamic conversion process. The receiving antenna can be designed to be 80% transparent so the surface underneath could be put to other uses. Receiving antennas would be located on land or offshore. A typical receiving antenna site will be 10 x 12 km. At least 100 potential sites in the United States could be considered.

4.2 Laser Power Transmission

Microwave power transmission is the present choice, based on considerations of technical feasibility, failsafe design and low flux levels, but laser power transmission is an interesting alternative because of considerable advances in laser technology over the past 10 years and the possibility of delivering power in smaller increments to individual receiving sites on Earth. The use of high-power lasers for laser propulsion and for power transmission between satellites is being investigated.\(^{14}\) Solar energy conversion, compatible with laser power transmission, may be carried out in GEO, or in lower orbits, particularly in a sunsynchronous orbit. If the latter orbit is to be used, a reflector will be required in GEO to reflect the laser power to a desired receiving site on Earth. The laser could be powered by photovoltaic or solar thermal conversion; or the solar energy could be used directly for laser pumping.

Although laser power transmission is in an early stage of development, it may have sufficient promise as an alternative to microwave transmission from space to Earth. The potential for misuse of laser power transmission and hazards through its use will have to be investigated because lasers may be perceived as either being dangerous or, under certain conditions, provocative.

5. SPACE TRANSPORTATION SYSTEM

To be commercially competitive, the SPS will require a space transportation system capable of placing large and massive payloads into synchronous orbit at low cost. The cost of transportation will have a significant impact on the economic feasibility of the SPS. The space transportation system which will be available during the early phases of SPS development for technology verification and component functional demonstration will be the space shuttle, now well along in development and to be demonstrated in space in the near future. Compared to the previously used expendable launch vehicles, it will not only significantly reduce the cost of launching payloads, but will also be a major step towards the development of space freighters of greatly increased
The space freighter, which may be either a ballistic or winged reusable launch vehicle, represents an advanced space transportation system with a planned capability to place payloads ranging from 200 to 600 metric tons into LEO. The space freighter will be recoverable and repeatedly reusable. The fuel for the lower stage will be liquid oxygen and a hydrocarbon; liquid oxygen and liquid hydrogen will be used for the upper stage. Both offshore and onshore launch facilities could be developed for the space freighter. Frequent launches (e.g., ten launches per day) will necessitate maintenance and overhaul procedures similar to those employed in commercial airline operations.

The space shuttle will be adequate to meet the SPS development requirements over at least a 10-year period. With space freighter development started in the late 1980’s, freighters would be available to launch a commercial SPS after 1996.

Personnel and cargo will be transported from LEO to GEO with vehicles specifically designed for this purpose. A modified space shuttle could be used to transport payloads from LEO to GEO. The material required for the SPS construction and assembly will be transported by a cargo orbital transfer vehicle which could be powered by ion thrusters of high specific impulse. Although the transit time to GEO could be measured in months, ion thrusters would minimize the amount of propellant to be transported to LEO.

Transportation costs of ballistic or winged-launch vehicles to LEO will be about $20/kg, including amortization of the vehicle fleet investment, total operations manpower, and propellant costs. The total cost per flight will be about $8 million, with vehicle production and spares accounting for 40%, manpower for 35%, and propellants for 25%.

6. ORBITAL ASSEMBLY AND MAINTENANCE

The absence of gravity and of the influence of forces shaping the terrestrial environment presents a unique freedom for the design of Earth-orbiting structures and provides a new dimension for the design of the structure required for the SPS, its fabrication, its assembly, and its maintenance in LEO and GEO. In GEO, the function of the structure is to define the position of sub-systems rather than support loads which under normal operating conditions are orders of magnitude less than those experienced by structures on the surface of the Earth. The structure will have to be designed to withstand loads imposed during assembly of discrete sections which may be fabricated in orbit and then joined to form continuous structural elements. The structure will therefore have to be designed to withstand both tension and compression forces which may be imposed during assembly and during operation when attitude control is required to maintain the desired relationship of the solar collectors with respect to the Sun and of the transmitting antenna with respect to the receiving antenna on Earth.

The immensity of the structure alone ensures that it would undergo large dimensional changes as a result of the significant variations in temperatures that will be imposed on it during periodic eclipses. During such eclipses, temperature variations as large as 200 K could be imposed, leading to substantial temperature gradients, which, depending upon the dimensions of the structure, would cause dimensional changes of 50 to 100 m if an aluminum alloy is used. Both aluminum alloys and graphite composites show promise for use as the structural materials. Graphite composites have a very small coefficient of thermal expansion compared to the aluminum alloys, but the aluminum structure could be insulated to reduce undesirable thermal effects.

The contiguous structure of the SPS is of a size which does not yet exist on Earth or in space. Therefore, unique construction methods will be required to erect the structures which are used to position and support the major components such as the solar arrays to form the solar collectors and the microwave subarrays to form the transmitting antenna. The basic approaches to constructing the required large space structure are as follows:

- Deployable systems, using elements fabricated on Earth;
- Erectable systems, using elements fabricated on Earth; and
- Erectable systems, using elements fabricated in space.

An automated machine capable of producing triangular truss shapes of desired sizes and material thicknesses in a modular configuration has been constructed. This automated beam builder consists of roll-forming units which are fed with coiled strip material and automatically impart the proper shape to the individual strip, weld and fasten the individual elements, control dimensions and produce the complete structural members. The machine can produce the structural member in increments of 1.5 m at a rate of 0.5 m/min for continuous production of structural beams in space.

Warehousing logistics and inventory control will be required to effectively manage the flow of material to the SPS construction facility, which will be designed to handle about 100,000 tons per year. The construction facility could be a large lightweight rectangular structure with dimensions of about 1.4 x 2.8 km. It would provide for launch-vehicle docking stations and 100-person crew cylindrical modules with dimensions of about 17 m diameter by 23 m long. The construction facility will be designed to assemble the solar energy conversion system and the microwave transmission antenna.

Construction costs, including transportation of the required construction crew of about 550 people and amortization of
the bases, are projected to account for about 8% of the total SPS capital cost. The construction crew's primary activity would be monitoring, servicing, and repairing, with little need for extra-vehicular activities. The SPS hardware throughput in the construction facility is projected to be 15t/hr, for a construction rate of one SPS per year. 10 The repetitive automated production process of space construction activities is projected to result in a productivity per crew member of 10 man-hours per ton of materials handled (the experience with terrestrial steel construction projects). To reduce the cost of space construction the production process will have to be equipment-intensive rather than labor-intensive. Thus the significant capital investments can be amortized over a number of SPSs.

7. SPS/UTILITY POWER POOL INTERFACE

The large power output potential of the SPS will require careful design of the utility power pool interface to reduce the impact on the stability of a total utility system. Electrical power grids are designed to provide this stability of power supply to the user by incorporating redundant installations of reliable equipment.

In addition to mechanical reliability, the reliability of the SPS will depend on generic system effects, and small variations (2-4%) caused by atmospheric absorption at the receiving antenna. Although the eclipse periods, occurring during the periods of minimum demand, are predictable outages, they are not planned outages since they are not deferrable. Thus, since they may affect the total system operation, they have to be included when calculating the forced outage availability of the SPS.

The stability of the SPS will have a substantial effect on the stability of the power pool which it serves. Low-frequency fluctuations could cause the power level delivered by the SPS to the receiving antenna to vary; high-frequency fluctuations could cause line surges which might disturb the transient stability of other generators in the power pool. The magnitude of these fluctuations will have to be investigated to establish the required degree of surge protection which would be supplied by short-term power storage (of the order of minutes) acting as a buffer.

These issues inherent in the SPS utility interface represent a significant influence on specific design approaches and selection of technology options.

8. SPS IMPACT CONSIDERATIONS

8.1 Economic

The economic justification for proceeding with a solar power satellite development program is based on a classical risk/decision analysis which acknowledges that it is not possible to know the cost of a technology which will not be fully developed for at least ten years — and the SPS plan calls for it to be commercialized, i.e., produced, operated and maintained, in not less than 20 years. Justification, of course, is equally difficult to provide for other large energy technology projects. This justification, therefore, requires an appreciation of the competitive cost of alternative energy sources for the generation of electrical power which would be available in the same period.

Any SPS development program should be timed-phased so that the “economic” purpose of each program segment will be to obtain information that will permit the decision makers to make a deliberate decision to continue the program or to terminate it — and thereby to control the overall risk. Cost-effectiveness analyses alone would be inappropriate, as they would require postulating scenarios of the future which could be extremely difficult, if not impossible.

The benefits and cost of a development program as large as the SPS are not likely to be uniformly distributed, but are more likely to be concentrated in certain segments of society and the economies of industrialized nations. Individuals, corporations, institutions, and even entire sectors of industry will react to the cost and the benefits of the development as they perceive them. As a result of these perceptions, political pressures are likely to have a pronounced effect on the SPS development program, its schedule, and its ultimate success.

In the various studies to date, the major emphasis has been given to establishing technical feasibility; only limited economic feasibility studies have been performed, primarily pertaining to system costs, development program costs, costs of terrestrial alternatives, and comparative economic analyses of space and terrestrial power systems. 17

8.1.1 Cost Projections

The economic viability of the SPS was compared with that of other alternatives to provide a basis for future decisions about a major SPS development program. The comparison indicated that if technology goals can be met, an operational 10-GW SPS would cost about $2,600 per kW once full production has been achieved and benefits of early experience have been incorporated in the design. 9

The SPS cost estimates are based on point designs and represent forecasts of future technology development which are unlikely to be precise. Risk analyses have been carried out to overcome the drawbacks associated with deterministic estimates. These analyses are based on the probable distribution of costs according to the present state of knowledge of the technology assumed for the SPS. Cost models were developed to determine unit production and operation and maintenance costs as a function of input variables. 17 A convergence of cost projections of the SPS indicates that capital costs would be in the range of $1,6000 to $3,500 per kW, leading to electricity costs, based on a 30-year lifetime and a
15% return on investments, as low as 30 mills per kWh, a nominal 60 mills per kWh and an upper bound of 120 mills per kWh. According to several accounting approaches, the costs of SPS power are in the competitive range of alternative power-generation methods. (Table 4.)

8.1.2 Institutional Impacts

Events have shown that controversies can arise over the utilization of existing energy technologies, even when they operate within well established performance and impact limits. In approaching the development of the SPS, the public response to its technology can be outlined only after the benefits and impacts of its performance are better defined. Although it is difficult to assess the institutional impacts of a concept like the SPS, which has not yet been demonstrated, even on a small scale, several issues are beginning to be explored and evaluated. Some of these deal with the potential damage to an SPS installation (which represents the concentration of massive amounts of capital and generating capacity) through accidents. Legal and political questions relate to impacts on telecommunications, both national and international, as well as the use of space and the rights of its use based on existing space law. A basic consideration will be the ownership of the SPS, the responsibility of the owners in case of accidents, from whatever causes, and the vulnerability of the SPS to actions of adversaries.

8.2 Environmental Impacts

The social costs of environmental impacts of this alternative large-scale power-generation system, including the land used for launch sites, and receiving antennas, and the aesthetic effects of such use, have to be established so that the benefits of each specific system approach can be weighed against potential dangers to human health, destruction of valued natural resources, and the intangible effects which may influence the quality of life.

8.2.1 Land Use

The receiving antennas could be located on a wide variety of terrain, ranging from desert to farm land and even in off-shore locations. In the United States, about 100 locations have been identified as potential sites for a typical receiving antenna with dimensions of about 10 km East-West and 12 km North-South — the exact dimensions will vary depending upon the latitude of the site. The microwave beam flux density at the edges of a site of this size would be 0.1 mW/cm².

Assuming that 100 5-GW SPS were to be put into operation, 100 receiving antenna sites would be required. This number of SPS would also require 10 launch sites, with each about 21 km². Table 5 compares the land use impacts of the SPS with other power generation methods.

8.2.2 Water Resources

On the assumption that the 100 receiving antennas would be constructed using conventional approaches, about 1.7 x 10⁶ metric tons of concrete would be used in the foundations. The concrete would require 2.3 x 10⁵ metric tons of water; the water would have to be available or brought to the site during the construction phase. Construction operation could damage the terrain, increase water run-off during storms and decrease the water supply to the local ecosystem. Construction in deserts could lead to modifications of the water cycle. Thus the impacts on water resources will have to be evaluated for each specific site.

The total non-recoverable water use at the SPS launch complexes over a life cycle of 30 years for 100 5-GW SPS would

<table>
<thead>
<tr>
<th>Power Generation Method</th>
<th>Land Use m²/MWe-Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal-Fired Steam¹</td>
<td>3600</td>
</tr>
<tr>
<td>Light-Water Reactor¹</td>
<td>800</td>
</tr>
<tr>
<td>Solar Thermal Conversion</td>
<td>3600</td>
</tr>
<tr>
<td>Photovoltaic Conversion</td>
<td>5400</td>
</tr>
<tr>
<td>SPS²</td>
<td>985</td>
</tr>
<tr>
<td>SPS³</td>
<td>675</td>
</tr>
</tbody>
</table>

Notes: 1. Includes Fuel Cycle
        2. Microwave Intensity of 0.1 mW/cm² at Receiving Antenna Site Perimeter
        3. Microwave Intensity of 1 mW/cm²

Source: Reference 20.
TABLE 6
HEAT RELEASE COMPARISONS OF NATURAL AND MAN-MADE ENERGY SOURCES

<table>
<thead>
<tr>
<th>Sources</th>
<th>Power</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcano</td>
<td>$10^5$ W/m$^2$</td>
<td>Global</td>
</tr>
<tr>
<td>Thunderstorm</td>
<td>100 W/m$^2$</td>
<td>2 cm/hr Rainfall</td>
</tr>
<tr>
<td>Lake Evaporation</td>
<td>100 W/m$^2$</td>
<td>Increased Downwind Rainfall</td>
</tr>
<tr>
<td>Large Industrial City</td>
<td>600 W/m$^2$</td>
<td>Climate Change</td>
</tr>
<tr>
<td>Suburban Community</td>
<td>4 W/m$^2$</td>
<td>No Detectable Climate Change</td>
</tr>
<tr>
<td>SPS Receiving Antenna</td>
<td>7.5 W/m$^2$</td>
<td>No Climate Change Projected</td>
</tr>
</tbody>
</table>

Source: Reference 9.

be about 6 mt/MW-yr. The water would be used to produce the hydrogen and oxygen rocket propellants and for rocket exhaust cooling. Hydrologic studies would be required to assure adequacy of water supply from local sources at each launch site. By comparison, a coal-fired power generating plant would require about 500 to 9200 mt/MW-yr of water.

The industries involved in the manufacture of the SPS would use about 250 x $10^6$ mt of solid material resources. The total water pollutants from manufacture would be about 0.2 mt/MW yr, including acids, bases, dissolved solids, suspended solids, organics and a measure of the biological oxygen demand and chemical oxygen demand. The total is small compared to the effluent from conventional electrical power plants. For example, a coal-fired steam power plant has total water pollutants of 6.7 to 630 mt/MW yr. A light-water reactor power plant of 35% cycle efficiency would discharge about 1.8 MW$\text{H}_{2}\text{O}$ to its cooling water for each megawatt of electricity generated and the pollutants in the cooling water would be transferred to either the surrounding local water or to the atmosphere. No cooling water is required at the receiving antenna because of the low heat release. (See Table 6.)

8.2.3 Air Quality

The generation of electrical power with the SPS would not — at least, directly — produce any air emissions or pollutants. But air pollutants would be produced in the mining, processing, fabrication, assembly and construction of the SPS, the receiving antennas, the space transportation system and the launch site complexes. Air pollutants would also be formed during the launch and boost of SPS payloads to LEO and during transfer from LEO to GEO.

The total environmental releases to the air would be small compared to fossil fuel electrical power plants and comparable to the non-radioactive air emissions resulting from light water reactor power plant construction. Large amounts of particulates would result from cement production and cement use. $\text{SO}_2$ would also be released during cement production and the production of steel and copper. CO would be released during the propulsion phase of booster flight and in the production of coke for steel and of thermal control coatings based on the use of carbon black. Hydrocarbons would be released in the production of coke, carbon black and the combustion of rocket propellants during launch to LEO. Nitrogen oxides would be produced during cement production and ammonia during the coke production process. Other pollutants would be released during the production of materials and during combustion processes. But the air releases of all those pollutants would be 0.405 mt/MW-yr which is insignificant compared to those of coal-fired steam plants, which range from 5.5 to 110 mt/MW-yr of operation. Therefore, the effects on public health of SPS air pollutants are projected to be minimal. Table 7 shows the resource saving and environmental effects avoided when energy is produced by 25 SPS's over a 10-year operating period as compared with the equivalent energy produced by coal-fired generating plants.18

8.2.4 Solid Wastes

No solid wastes would be produced during the generation of electric power by the SPS. Solid wastes would only be formed during the manufacture and construction of the SPS, the receiving antenna and launch sites and the space transportation system. They would amount to about 0.1 mt/MW-yr, primarily attributable to aluminum, steel and silicon production. The amounts are negligible compared to the 890 to 2100 mt/MW-yr from a coal-fired steam electrical plant.

8.2.5 Noise Impacts

The primary noise impacts would be at the launch complexes during the frequent launches of the launch vehicles while the SPSs are being constructed. Noise will also be generated during launches of various vehicles to supply the SPS with expendables and for their maintenance, but these launches would be less frequent. Noise impacts during the
TABLE 7

RESOURCE SAVINGS AND LAND AND AIR POLLUTION AVOIDED USING ENERGY GENERATED BY 25 SPS'S OVER A 10-YEAR OPERATING PERIOD

Equivalent United States Energy Generated by Coal:

Resources Consumed —
- Eastern Province Coal (13,000 Btu/lb)
- Central Interior Province Coal (11,400 Btu/lb)
- Northern Province Coal (8,400 Btu/lb)
- Limestone Consumption (for Desulfurization if used)

Environmental Effects —
- Land Altered by Strip Mining (if used)
- CO₂ Emission
- Sulfur Emission (max. per NSPS*)
- Nitrous Oxide Emission
- Particulates Emission
- Asbestos, Lead, Selenium & Mercury Emission

<table>
<thead>
<tr>
<th>Resource</th>
<th>Equivalent United States Energy Generated by Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Province Coal</td>
<td>7 Billion Tons</td>
</tr>
<tr>
<td>Central Interior Province</td>
<td>8 Billion Tons</td>
</tr>
<tr>
<td>Northern Province Coal</td>
<td>11 Billion Tons</td>
</tr>
<tr>
<td>Limestone</td>
<td>700-1100 Million Tons</td>
</tr>
<tr>
<td>CO₂ Emission</td>
<td>900 to 2100 Square Miles</td>
</tr>
<tr>
<td>Sulfur Emission</td>
<td>20-30 Billion Tons</td>
</tr>
<tr>
<td>Nitrous Oxide Emission</td>
<td>110 Million Tons</td>
</tr>
<tr>
<td>Particulates Emission</td>
<td>~60 Million Tons</td>
</tr>
<tr>
<td>Asbestos, Lead, Selenium &amp; Mercury Emission</td>
<td>~9 Million Tons**</td>
</tr>
<tr>
<td></td>
<td>~122 Thousand Tons**</td>
</tr>
</tbody>
</table>

*New sources performance standards.
**Typical of central interior province coals.

Source: Reference 18.

construction of the receiving antennas would be minor, because the sites would be remote from populated areas.

The launch complex sites would most likely be located in the less populated Southwestern region of the United States. An international cooperative effort, however, could lead to the selection of launch complexes nearer the equator where there are large uninhabited land areas.

8.2.6 Microwave Beam Effects

8.2.6.1 Atmospheric Attenuation and Scattering

Attenuation of the microwave beam by rain, cloud droplets, snow, and hail will depend on their size, shape, and statistical distribution and composition. Rain, wet snow, melting precipitation and water-coated ice attenuation is low at frequencies below 3 GHz. The most severe condition is expected in rain clouds, where attenuation may reach 4% at 3 GHz. The attenuation produced by a 1-km path through wet hail could reach 13% at 3 GHz.

Forward scattering by rain and hail will increase the field intensity outside the main microwave beam. For example, a 5-GW SPS operating at 3 GHz would scatter 3 mW nearly isotropically if the storm cell height were 1 km. At a range of 10 km, the scattered microwave beam power density would be about 2 x 10⁻⁴ mW/cm². Therefore, scattering by rain or hail is not expected to significantly increase sidelobe levels or broaden the main microwave beam.

8.2.6.2 Ionospheric Propagation

Among the several possible interactions of the microwave beam with the ionosphere are the following:

- Ambient refraction of the microwave beam by the ionosphere — This effect leads to a negligible displacement. If horizontal gradients are present in the ionosphere, they could result in displacements (less than 100 meters) of the microwave beam.

- Ionospheric electron density irregularities — These self-induced or ambient irregularities will cause phase fluctuations (less than 10 degrees) across the wave front of the reference beam propagated from the center of the receiving antenna to the transmitting antenna face. Random phase variations will subside within a few hundred meters and within tens of seconds.

Power beam dispersion due to ionospheric density fluctuations will increase the field intensity at the beam edges by up to 30%. At low power densities, these fluctuations at the edges of the beam will not cause any significant power
8.2.7 Stratospheric Pollution by Space Vehicle Exhaust Products

The potentially harmful effects of supersonic and space shuttle transport exhaust in the stratosphere are receiving considerable attention.

Injections of water vapor and NOX (which are involved in the complex sequence of chemical reactions governing the abundance of ozone in the region from 20 to 35 kilometers) are projected to result in a reduction of the mean abundance of ozone, although there is still uncertainty regarding the roles of each of these components. The actual effects of any given rate of injection of either of these two components are difficult to determine because of uncertainties regarding the vertical and horizontal movements in the stratosphere which govern the rate at which they are injected, distributed and ultimately removed from it, the lack of experimental observations on space vehicle emissions, the composition of the stratosphere as a function of altitude, location over the surface of the globe, and the nature of the chemical and photochemical reactions which determines the abundance of chemical species involved in the ozone equilibrium. Because vertical mixing in the stratosphere is very slow (about 2 years at 20 km and 4 to 20 years at 50 km), and declines with increasing altitude, gases injected into the stratosphere will accumulate even at a low annual rate of injection and could yield a large equilibrium value at very high altitudes. (The region from 50 to 100 km contains only 0.1% of the total mass of the atmosphere.)

Although the chemistry of water vapor in the upper stratosphere has been studied, there is uncertainty regarding the possible consequences of incremental additions of water vapor. Water vapor is photodissociated to form radicals and molecules which will react with ozone and molecular and atomic oxygen. Furthermore, changes in the water vapor content could influence the natural flux of NOX to the level of the ozone layer. Consequently, the effects of the space transportation system on water vapor injection, particularly in the upper stratosphere, require further investigation.

8.2.8 Microwave Biological Effects

The designs of the transmitting antenna and receiving antenna are strongly influenced by the choice of the power distribution within the microwave beam and determine the level of the microwave beam power density at the edges of the receiving antenna site. Acceptable guidelines for continuous low-level exposure to microwaves must be used.

At present, there is a considerable difference of scientific opinion on the appropriate exposure levels to microwave radiation. Exposure guidelines adopted by several nations differ sharply. In the United States, microwave radiation protection guidelines, first proposed in 1953, were based on physiological considerations — i.e., continuous whole body exposure of a human subject resulting in a maximum equilibrium temperature rise of 1°C. This guideline was accepted by U.S. Government agencies and industry as tolerable on a long-term basis without risk of irreversible damage. Experimental results on animals exposed to microwave radiation indicated that irreversible tissue damage occurred at power densities of about 100 mW/cm². Based on the premise that thermal effects predominate at levels higher than 10 mW/cm² and that below this power density level, nonthermal effects predominate, the American National Standards Institute recommended in 1966 that 10 mW/cm² be used as an acceptable standard.

The USSR microwave Exposure Standards rest on the empirical findings by Soviet scientists that microwave exposure affect the nervous systems of animals and humans. Their studies indicated that the central nervous system is particularly sensitive to microwave radiation, and that chronic occupational exposure of humans to very low power microwave radiation leads to a variety of psychological and physiological effects.

In view of the current interest in low-level effects of microwave radiation, it is very likely that international standards will be adopted in time to be incorporated in the SPS design. The basic premise is that the SPS microwave transmission system must be designed so that the microwave power flux densities to which the public would be exposed outside the receiving antenna site will meet international standards.

The SPS microwave transmission system design incorporates the principle of retro-directive control of the microwave beam to make it impossible for the beam to be pointed to any location but that of a receiving antenna, instantaneous shut-off of power fed to the microwave generators and graceful system failure modes. (See Figure 3.)

Until acceptable international standards have been agreed upon, a microwave power flux density of 0.1 mW/cm² at the perimeter of the receiving antenna site has been assumed for the system design studies. The effects of either an increase or decrease in the permissible microwave power flux density based on international standards can be evaluated in two ways: system design parameters and economic factors.

8.2.9 Radio Frequency Interference

Worldwide communications are based on internationally agreed upon and assigned frequencies. Because the frequency bands spanning the most desirable operating frequency of the SPS are already in heavy use, the potential for radio frequency interference (RFI) of the SPS with existing communication systems is high. The microwave generators will have to be designed to filter out most spurious outputs. RFI could occur during the shutdown of the microwave gener-
100 r

U.S. Standard for Continuous Exposure to Microwaves

Normal Operation of Phase Control System

Partial Failure of Phase Control System

Eastern European Standards

0 5 10

Receiving Antenna Radius, Km

Source: Reference 9.

FIGURE 3 EFFECTS OF PHASE CONTROL ON MICROWAVE POWER DISTRIBUTION AT RECEIVING ANTENNA

ators or result from fundamental microwave frequencies and its harmonics, random background energy, and other superfluous signals. Although RFI can be controlled by the selection of frequency, narrow band operation, and use of filters, detailed and specific effects and impacts on radio astronomy, shipborne radar, and communication systems will have to be determined before the international acceptability of specific frequency allocations can be assured. The RFI effects and international agreements on frequency assignments are issues that will have to be faced at various stages during the SPS development, and will be discussed at the World Administration Radio Conference, Geneva, 1979.

8.2.10 External Energy Subsidies

In addition to other economic comparisons the external energy subsidies which are required to place an SPS in operation have to be considered, inasmuch as they determine how long a power plant would have to operate before all of the energy required — i.e., to process the materials, fabricate and assemble components and place the power plant in operation, including space transportation and the required propellants — would be paid back during normal operations. Figure 4 shows the external energy subsidies for a variety of present and future power plants.

The shaded area of the bar represents the subsidy required for initial construction (capital subsidy) and the unshaded portion of the bar indicates the subsidy required for annual operation and maintenance (operating subsidy).

On an energy subsidy basis, achievement of the system design goals would make the SPS very competitive with other systems. The results of the analyses of external energy subsidies based on a 30-year lifetime of the SPS can be translated into a 3.25-year energy payback time for the SPS, including the operating subsidy. Recent impact assessments indicate that energy payback will be achieved in 1.6 years.

Because the GEO environment is benign compared to the terrestrial environment, with properly scheduled maintenance the projected lifetime of the SPS will be of the order of hundreds of years.

FIGURE 4 COMPARISON OF EXTERNAL ENERGY SUBSIDIES FOR ALTERNATIVE POWER PLANTS

9. SPS DEVELOPMENT PROGRAM

The stage is set to embark on a more intensive evaluation of the SPS option, including key terrestrial tests required to support system studies, to define the SPS development and operational phases, and to initiate supporting space experiments that will provide crucial information on which to base decisions concerning required technology and its impacts. The objectives of the near-term SPS development program are to:

1) Identify and assess issues that could constrain successful SPS development, and

2) Seek ways to resolve these issues with a combination of analyses, system studies and experiments on Earth and in space.

The SPS development program can be divided into three overlapping phases, as follows:

- Phase 1: Concept Feasibility Studies — The objective of the present studies, which started in 1972, is to establish the overall feasibility of the SPS concept through system defini-
The potential of the SPS to meet future energy demand is being recognized and plans for its development are being studied. As great a technological challenge as the SPS is, no reason has yet come to light for concluding that it could not be built and operated successfully. Indeed, there is growing confidence in the technical community that, given the resources for the task, the SPS could be built and would work. How well it would work, for how long, with what societal impact, and at what cost is yet to be determined.

It is desirable to determine whether or not the SPS concept is a sufficiently attractive long-term energy supply option to warrant development. That decision, as with any other energy supply option, should be made as soon as it is possible to do so rationally, so that energy policy and planning for the various competitive options can be based on reasonably confident knowledge of their key characteristics. Therefore, an aggressive concept and innovation and technology verification program should be initiated and conducted in parallel with programs which support the other energy supply alternatives so that the necessary rational comparisons with alternative sources can be made more or less simultaneously.

The SPS is one of the most promising power generation options which could contribute to meeting global energy demands in the 21st century. Its successful implementation (together with terrestrial solar energy conversion methods) could lead to the elimination of energy-related concerns. The successful development of the SPS would counteract the trends toward a stagnant society with prescribed limits to growth, and an aversion to risk taking. Therefore, in a broader sense, the development of the SPS goes counter to the frame of mind where every new technological development is “viewed with alarm” rather than “pointed to with pride” as an accomplishment. Our civilization has successfully unlocked the last frontier – space – which promises to lead to the extension of peaceful human activities beyond the confines of the Earth’s surface. On the basis of the increasing confidence in the feasibility and promise of the SPS, this option deserves serious consideration as humanity faces the challenges posed by the inevitable transition to renewable sources of energy.

10. CONCLUSIONS

The potential of the SPS to meet future energy demand is being recognized and plans for its development are being studied. As great a technological challenge as the SPS is, no reason has yet come to light for concluding that it could not be built and operated successfully. Indeed, there is growing confidence in the technical community that, given the resources for the task, the SPS could be built and would work. How well it would work, for how long, with what societal impact, and at what cost is yet to be determined.

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REFERENCES


