An Overview of the Solar Power Satellite Option

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***Abstract*—The objective of the solar power satellite (SPS) is to convert solar energy in space for use on Earth. Its most significant benefit is the potential for continuously generating large-scale electric power for distribution on a global basis. While there has been no SPS development program in the United States since 1980, it has continued to be investigated in several countries. The SPS system is outlined and the status of the SPS concept development is reviewed. Results of assessments of key issues are reported including economic considerations and environmental issues such as health and ecological effects of microwave beaming, non-microwave health and ecological effects, beam effects on the atmosphere and ionosphere, and electromagnetic compatibility, as well as physical resource requirements including land use, materials availability and energy pay-back periods. Legal issues and the need for international agreements on SPS operations are outlined. International SPS-related activities are discussed within the context of evolving space programs with the focus on Europe, Japan and the former U.S.S.R. An approach for an evolutionary advancement of SPS to meet requirements for power supplied at first for use on Earth and in space is presented, and a growth path to achieve the potential of power from space for use on Earth is outlined. The significance of advancements in technologies applicable to the development of the SPS as an alternative energy option for use on Earth, and as a potential stimulus for space infrastructure evolution, including the use of extraterrestrial resources, are discussed.**

Introduction

THE WORLD is encountering a "shifting of history's tectonic plates" [1]. The fundamental changes occurring in the global economy, the uncertainties brought about by the disintegration of the Soviet Union, and the efforts to create a United Europe are resulting in the reevaluation of the 21st Century world order. Viable options must be provided to meet increasingly insistent demands for higher living standards of the exponentially growing global population, and to forestall instabilities leading to military confrontations with potentially disastrous results.

Key to the achievement of a new world order will be the development of energy resources at a societally acceptable and economically affordable cost within a realistic planning horizon. This must be the theme for the future development of all energy sources whether based on fossil, nuclear or renewable resources. The significance of the SPS concept within the context of meeting global energy demands, and in consonance with this theme is its potential to meet not only growing global needs for electricity, but also to replace fossil and nuclear fuels. The SPS will be a macroproject when there is a consensus regarding its benefits for humanity. Macroprojects are distinct when compared to all other enterprises by virtue of the deployment of advanced technology and processes that were previously demonstrated on a much smaller scale, the magnitude of the required investments with returns on such investments extending over a time frame not customary in conventional projects, and with expected societal benefits to large regions, groups of nations, or globally.

There is an opposing view how best to meet future energy demands based on the development of appropriate technology utilizing distributed, small-scale, renewable energy sources. Appropriate technology is a concept based on the view of a world of small, largely self-sufficient communities following the Jeffersonian model but hardly a realistic goal for the world community of the 21st Century [2]. The technical, economic and societal dilemmas of large-scale engineering projects have been recognized by E. F. Schumacher, [3] but not considered always and inevitably "inappropriate." As Schumacher points out: "It depends on what we are trying to do."

The SPS System

As originally conceived [4] an SPS could utilize various approaches to solar energy conversion. Among these conversion processes, photovoltaic conversion was selected as a useful starting point because solar cells were already in wide use in communication, Earth observation and meteorological satellites, both in low-Earth orbit (LEO) and in geosynchronous orbit (GEO). Since then, an added incentive has been the substantial progress being made in the development of advanced photovoltaic materials, microwave and laser power beaming, and the increasing confidence in the achievement of significant cost reductions in space transportation, and in the use of lunar materials envisioned as part of the Space Exploration Initiative [5].

In the SPS concept, solar cell arrays would convert solar energy directly into electricity and feed it to microwave generators forming part of a planar, phased-array transmitting antenna. The antenna would direct a microwave beam of very low power density precisely to one or more receiving antennas, at desired locations on Earth. At the receiving antennas, the microwave energy would be safely and efficiently reconverted into electricity and

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then transmitted to users. An SPS system could consist of many satellites in Earth orbits, e.g., in GEO, each SPS beaming power to one or more receiving antennas at desired locations.

In the 1970's, SPS assessments were performed by the Congressional Office of Technology Assessment [6], and the National Research Council of the National Academy of Sciences [7]. These assessments considered technical, economic, environmental and societal issues. In preliminary studies of the SPS concept (1968 to 1972), a plan for an SPS R & D program was outlined [8]. In 1972, a feasibility study was undertaken to evaluate an SPS design for a power output of 5 GW for use on Earth [9]. This feasibility study identified key technological, environmental and economic issues for further study and provided the foundation for more extensive system definition studies [10]–[12]. An assessment of the SPS concept was the objective of the SPS Concept Development and Evaluation Program (CDEP) [13]. "To develop, by the end of 1980, an initial understanding of the technical feasibility, economic practicality, and societal and environmental acceptability of the SPS concept."

This assessment indicated that no single constraint has been identified which would preclude the development of an SPS for either technical, economic, environmental or societal reasons, and that the NASA SPS Reference System which assumed that 5 GW of base load power would be generated at the receiving antenna on Earth demonstrated that the technology for transmitting power from space to Earth is amenable to evolutionary development, and that the SPS concept is technically possible.

In the 1980's, the applications of extraterrestrial energy and materials resources to meet future global energy needs were of increasing interest [14]. The challenges to develop the SPS capable of using lunar resources are formidable. International efforts including demonstration projects will be required over a period of decades to make the transition from the current SPS design concepts to designs that can use lunar resources or could be deployed on the lunar surface [15].

Economic and Societal Assessment Issues

Economics: Detailed technical assessments of the SPS system were performed as part of the CDEP by the U.S. Department of Energy and NASA [13] for both microwave and laser beam transmission, with positive results. The CDEP addressed economic and societal issues in considerable depth because they are the key to future SPS development as summarized below.

The economic justification for an SPS development program must acknowledge that it is not possible to know now the cost of a technology which will not be fully developed for at least 15 years or commercialized in less than 20 years. Justification is equally difficult to provide for other advanced energy technologies.

Cost-effectiveness analyses alone are inappropriate because they would require the extremely difficult task of postulating credible scenarios of the future. The near-term decisions regarding the planning for an SPS program should be based on the resources allocated to the SPS development tasks and their priorities rather than the projected economics of the SPS in the 21st Century.

Cost projections do not provide meaningful estimates of the potential market penetration of the SPS or alternative energy supply technologies because the uncertainties in forecasting prices are much larger than the cost differentials on which the cost comparisons among competing technologies will eventually be based. However, such cost studies provide estimates of the delivered cost of power to indicate whether the SPS has any chance of being competitive, identify the major cost elements so that program efforts can be properly focused to reduce the projected costs, develop a consistent framework to evaluate different technological options, determine the impacts of raw material requirements and availability on cost and the effects of a development program on labor costs and capital markets, and assess the cost risk in comparison with alternative energy supply technologies, including environmental impacts and societal effects.

The SPS was compared with alternative energy technologies, including coal, nuclear and terrestrial photovoltaic systems, in terms of cost and performance, health and safety, environmental effects, resource requirements, and institutional issues [16]. The assessments indicated that:

- The life-cycle cost range for the SPS overlaps the competitive cost ranges of alternative energy technologies;
- All the technologies considered will have distinct, though different, health and safety impacts;
- The low-level and delayed impacts of all energy technologies are difficult to quantify and assess;
- Each technology has material requirements that could be critical, because of environmental control standards or limited production capability; however, these requirements do not appear to limit the SPS;
- The total amount of land required for the complete fuel cycle is roughly the same for all energy technologies; however, the SPS and terrestrial centralized photovoltaic systems would require large contiguous land areas, although SPS receiving antennas could be placed on off-shore floating structures.
- The SPS, fusion and other advanced energy technologies may be difficult to operate within the current regulatory environment; however, the SPS would also be subject to international regulations that may also apply to other energy technologies.

The Department of Energy and NASA SPS program was unique in that for the first time a technology development program focused not just on key technology issues but was also concerned with environmental effects, comparative economic factors, societal issues and program risks and uncertainties before any commitment to a development program was made [17]. Among these considerations the most significant non-technical issues where the SPS's environmental effects and resource requirements.

Environmental Effects

The key environmental effects associated with the SPS are those which could affect human health and safety, ecosystems, climate, and interactions with electromagnetic systems.

Health and Ecological Effects of Microwave Power Transmission: At the perimeter of a receiving antenna, the public would be exposed to microwaves at a power density of 0.1 mW cm^{-2}. If as assumed for the NASA SPS reference system, 60 receiving antennas in the continental United States were spaced an average of 300 km apart, the minimum power density at any point beyond the antenna location would be about 10^{-4} mW cm^{-2} [18]. In the former USSR, the maximum value for continuous, 24-hour, exposure of the general public was estimated to be 10^{-3} mW cm^{-2}. The workers within the receiving antenna area would not be exposed to levels exceeding U.S. guidelines for occupational exposure with suitable precautionary measures. The fact that large populations have been exposed to microwave energy from communications, medical, radar and industrial processes for many decades and, more recently, from 250 million microwave ovens, without demonstrated adverse effects on human health and the ecosystem, is an indication that microwaves beamed from space to Earth are unlikely to result in undesirable health and ecological effects, although research of such effects on biota (e.g., birds, should be continued [19]).

Non-Microwave Health and Ecological Effects: Among the various space-related activities only the exposure of the space workers to ionizing radiation appears to present a major health risk. Most of the other health and ecological effects of the construction and operation of receiving antennas and launch sites have conventional impacts which would be controlled or mitigated by appropriate engineering solutions, and are analogous to developing and constructing alternative energy sources.

The risks from ionizing radiation to space workers could be minimized through carefully designed shielding for space vehicles, for working and living modules and by the provision of solar storm shelters. Of greatest concern in GEO are the high-energy, heavy ions emanating from galactic radiation which may result in exceeding recommended exposure limits for workers. More data are required to establish the expected ionizing radiation environment in GEO to guide the design of measures to limit exposure of space workers.

Effects on the Atmosphere: Weather and climatic effects of waste heat released at a receiving antenna site would be generally small, comparable to the heat released over suburban areas. The absorption of microwave power in the troposphere is expected to increase during heavy rainstorms, but even then would have only a negligible effect on the weather. The air quality effect of the launch of advanced space transportation vehicles, which would increase sulphur dioxide concentration, would not be critical. Nearly all of the carbon monoxide would be oxidized to carbon dioxide, and the amount of nitric oxides formed would be negligible. The change in the globally averaged ozone layer due to SPS launches would be undetectable as would the effects of nitrogen oxides. Transient clouds at stratosphere and mesosphere altitudes could be induced in the vicinity of the launch site, but they would not be expected to have a detectable impact. Some acid rain might occur near the launch site if there are significant quantities of sulphur in the fuel. Inadvertent weather modification by rocket effluents in the troposphere, because of cumulative effects, would be possible and would require continuing monitoring of rocket exhaust clouds and the various meteorological conditions to mitigate such effects.

The effect of rocket launches on the ionosphere could be mitigated by a depressed launch trajectory, for example, a booster returning below an altitude of 75 km would keep the rocket effluents in the turbulent mixing regions of the atmosphere, reduce the possibility of hydrogen diffusion into the ionosphere and prevent the formation of noctilucent clouds. Optimization of the first stage's launch trajectory would reduce the injection of water vapor into the lower atmosphere if hydrogen-oxygen propellants are used; however, water vapor deposited in the upper atmosphere will have a long residence time, and may result in undesirable effects if large quantities of water are deposited over an extended time frame.

The use of lunar resources would reduce the need to launch commodity materials from Earth by 90%, and therefore deserves detailed consideration as part of the Space Exploration Initiative. Launches from Earth would be used primarily for high unit value payloads, and to support manned construction activities in orbit.

Ion thrusters controlling the position of the solar energy conversion system and the microwave transmission antenna would inject argon ions into the plasmasphere and magnetosphere. The impacts of these effects are uncertain. Their magnitude would have to be established and perhaps other ion-thruster propellants utilized to minimize any disturbance of the plasmasphere or changes in the magnetosphere interaction with the solar wind.

Effects of Ionospheric Disturbance on Telecommunications: The ionosphere is important to telecommunications because radio waves can be totally reflected and returned to the Earth's surface, depending on the ionospheric electron density, the frequency of the electromagnetic energy, the frequency of occurrence of electron collisions, and the strength of the geomagnetic field. Changes in the ionosphere can alter the performance of telecommunication systems, and small-scale irregularities can produce radio signal fading and result in loss of information. Ionospheric changes could result either from heating of the ionosphere by the microwave beam or the interactions with effluents from space vehicles. The effects of rocket exhaust effluents during launch can be reduced through appropriate trajectory control. However, during reentry of the recoverable booster and orbiter stages, ablative materials and oxides of nitrogen could affect a small portion of the ionosphere.

Experiments on the effects of microwave beam heating of the ionosphere have indicated that at a peak power-density of 23 mW cm^{-2}, the microwave beam would not adversely affect the performance of telecommunication systems and that the power density could be doubled [20]. Because of equipment limitations, these experiments deposited power only in the lower ionosphere comparable to the microwave beam power densities. Modified and expanded facilities would be required to simulate heating of the upper ionosphere, verify the existing frequency-scaling theories, and establish the effects of the microwave beam on the upper atmosphere. If no adverse heating effects are observed, the peak power density could be increased.

Electromagnetic Compatibility: The SPS must be designed and operated to satisfy established national and international requirements for uses of the electromagnetic spectrum. There is a potential for producing interference because the amount of microwave power transmitted from space to Earth would be unprecedented and the size of the microwave beam of the SPS reference system would be about 7 km at the Earth's surface. It could interfere with public communications, military systems, radar, aircraft communications, public utilities, transportation systems communication, other satellites, as well as radio and optical astronomy. The interference potential of the microwave beam would not be especially unusual except in the extent of the geographic area affected. High-power radar systems produce interference of similar electromagnetic intensities, but over limited areas. Shielding and radio receiver filters are commonly used to avoid interference and could be adapted for this purpose.

The dimension of SPS-caused interference by direct energy coupling to any class of equipment is part of the engineering design of the microwave power transmission system and the receiving antenna. Interference can be minimized by designing the microwave system to stringent specifications, to reduce undesirable emissions at frequencies other than its operating frequency and to constrain the size and shape of the transmitted microwave beam. Careful receiving antenna siting, including tradeoffs between locations of the antennas near energy load centers, could avoid interference with most other users of the radio spectrum. SPS will not interfere with other satellites in GEO, such as communication satellites, because the microwave beam would deliver less than one-fifth the power that would be required to produce interference [21].

Radio and optical astronomical observations have to measure weak signals. Such observations could be significantly inhibited by the microwave power beam, even at distances of hundreds of kilometers from the receiving antenna sites. One mitigating approach would be to construct radio telescopes on the far side of the moon, where they would be shielded from all forms of terrestrially produced electromagnetic interference. Earth-based optical observations would be hindered by light reflected from the surfaces of an SPS, which would have a brightness approaching that of Venus when it is most visible, unless surfaces are coated so as to reduce their reflectance. Orbiting astronomical observatories could be constructed which would provide better observational conditions than those obtainable even in the best locations on Earth. The cost of these mitigating approaches may have to be charged to the global SPS system.

Resource Requirements

The physical resource requirements are land use, materials availability, and energy utilization.

Land Use: Receiving antenna siting studies [22] showed that there are many suitable locations for receiving antenna sites throughout the United States. The methodology developed for determining eligible areas for receiving antenna sites is widely applicable; however, actual acquisition of specific sites may be difficult, and location of sites in some areas could, because of their topography, incur a heavy cost penalty for site preparation and perhaps even modifications of the receiving antenna designs. Although studies showed that there are no apparent undesirable biological effects of microwaves on birds [23], selection of sites to avoid migratory bird flyways would be possible.

The sheer size and intensity of use of the contiguous land area required for a receiving antenna site and site construction will have significant implications for environmental, societal and economic impacts, and these will have to be established for each specific antenna site. In addition, the secondary uses of selected receiving antenna sites for agricultural purposes or for terrestrial solar energy conversion will need to be assessed. The alternative of locating the receiving antenna offshore may be attractive for major population centers which are located near the sea coasts not only because of their possible proximity but also because floating offshore structures may be competitive with land-based structures and provide an opportunity for mariculture [24]. For example, the Northeast region of the U.S. has the smallest potential land area for receiving antenna sites relative to projected needs. An offshore floating structure would provide 5% of the fish requirements of the U.S. with mariculture, which already is being successfully used for salmon production in Norway.

Materials Availability: An analysis of the materials requirements for the construction of the SPS indicated that no insurmountable materials supply difficulties are evident in terms of world and domestic supply and potential manufacturing capacity [25]. Over one-half the materials for the SPS reference system are readily available, but there are potential supply constraints on tungsten, silver and gallium. The industrial infrastructure to fabricate SPS components such as ion thrusters, dipole rectifiers, microwave generators, and graphite composites will be adequate; however, solar cell arrays will require development of mass production technologies. These are already being developed to meet terrestrial photovoltaic system requirements and could be used also for the SPS. Use of lunar resources would replace most commodity materials required for SPS construction.

Energy Utilization: Net energy analysis is useful in comparing alternative energy technologies in terms of the energy produced by each system per unit of energy required. When fuel is excluded, the energy ratios for the SPS reference system are marginally favorable with respect to other energy production methods. When fuel is included, the SPS energy ratios are very favorable [26]. Using the technologies of the SPS reference system and estimates based on their probable improvements, energy payback periods for the SPS would be about one year [27]. The energy payback is even more favorable when secondary effects of air pollution and CO_2 release into the atmosphere are considered.

Legal Issues

The 1967 Space Treaty, Article VII, stipulates that each state is "internationally liable for damages" to others caused by activities in space. The 1973 "Convention on International Liabilities for Damages Caused by Space Objects" amplifies these responsibilities.

The existing space law implies that if the global or local environment is damaged through SPS system operation, the SPS owners might face lawsuits or other forms of grievance procedures. Even if operation of an SPS system had no other effect than that caused by a nation making use of the power supplied to it, the design of a globally marketable SPS system to meet widely varying national standards could add significantly to costs. Furthermore, the possibility of law suits could make insurance expensive or impossible to procure, unless the development, construction, operation, and monitoring of the SPS system would be undertaken within the framework of international agreements.

Such agreements would also ensure the peaceful uses of the SPS. The U.N. Committee on the Peaceful uses of Outer Space, the International Telecommunication Union, and the Committee on Space Research of the International Council of Scientific Unions are examples of the organizations that could evolve policies for organizations to develop and operate an SPS system. The principles embodied in international agreements will require a sense of participation for all nations that could benefit from the operations of the SPS system, and a consensus regarding the future course of SPS development. Intelsat and Inmarsat are examples of international cooperation and agreements that may be appropriate for an organization operating a global SPS system.

A pressing legal issue is frequency assignment to potential users of the electromagnetic spectrum, and geosynchronous orbit positions. For example, the 2.45 GHz region of the industrial, scientific and medical (ISM) band is essential for microwave power beaming because of the low absorption in the atmosphere in this region. Other potential users are petitioning the FCC to permit segments of this unique band to be used for communications. Encroachment on the ISM band by other users would have significant undesirable effects, such as, increased complexity of microwave power generation, transmission and reception leading to higher costs and reduced power beaming capabilities.

International SPS-Related Activities

The U.S. competitive edge in SPS and power beaming related activities pioneered by the aerospace industry, NASA, and the Department of Energy is eroding. At this time there is no U.S. government program concerned with civilian applications of power beaming or SPS; however the Office of Space Energy that has an interest in power beaming, was established in 1991 in the Department of Energy.

Following the U.S. lead, several space-faring countries have engaged in planning efforts and studies devoted to power beaming recognizing the importance of applicable technologies to the development of the space infrastructure, commercial uses of space, space exploration, and the largest single market on Earth—electrical power generation.

Europe: The first International Symposium on the "Solar Power Station in Space" was organized by the International Microwave Power Institute, and held in Scheveningen, Netherlands, October 5, 1970 [28]. Participants included representatives of European, U.S. and U.S.S.R. organizations.

French government organizations have been engaged in a multi-year study of space power systems since 1982, including the analysis of long-term space missions that use more than 100 kW.

The "SPS 91-Power from Space" symposium was held in Paris, August 27–30, 1991, organized by the Societe de Electriciens et des Electroniciens, sponsored by the French Minister for Research and Technology, and 25 international organizations including the United Nations, and attended by 215 representatives from 17 countries who contributed 110 papers.

The consensus of the participants was that power beaming is realizable now starting with near term power beaming applications, and that power from space represents one of the few globally applicable options to meet 21st Century energy requirements of the global population that is projected to reach 10 billion by mid-century.

The Future Prospects Group of Eurospace, Paris, was founded in 1981, with the aim to address topics of interest for the future of the Eurospace Community. Participants include major European aerospace companies. As a result of the renewal of interest in SPS for generation of electricity in space and power beaming to elements of the space infrastructure and terrestrial electrical distribution networks, the Group started in 1990 the exploration of the applications of SPS. The goal of this effort was to verify the validity and economic feasibility of the SPS concept, and to take this option into consideration in the definition of the next generation of European space programs. The Group concluded that the SPS is of considerable interest, first because of a need for modest electrical power sources for space applications (in the range of tens of kW), and secondly because of the longer term prospects of the SPS for space and terrestrial applications. The group recommended that utilities cosponsor a series of experiments and pilot operations in the future.

The specific subject of interest to European organizations is the preparation of transmission demonstrations that could be performed on board Eureca or Spacelab around 1997. Although the focus is on a specific objective, this does not mean that Eurospace is losing sight of the other aspects of the POWERSAT program including pre-operational systems, and other opportunities for experiments that can be developed in the European context or in an international cooperative framework. This initiative is in line with the European efforts to develop energy production methods that are based on renewable resources including hydrogen production as fossil and nuclear fuels will be difficult to bring on line.

Japan: Japan is currently building its own launch vehicle, designated H II, which will use the more efficient liquid hydrogen/liquid oxygen fuels. The initial version of this vehicle will have limited lift capability, but it is the forerunner of larger launch capacity vehicles.

The International Space University, Cambridge, MA has been invited to hold its 1992 summer session in Kitakyushu, Japan, which will have as its major student project focus the SPS. Recently, the Institute of Space and Astronautical Science (ISAS) has evolved a concept for a 10 MW SPS in a 1000 km orbit to demonstrate the feasibility of space power. At this orbital altitude up to 33 SPS's can be orbited so that all the receiving antennas can receive power from space constantly from early morning to early evening.

The Ministry of International Trade and Industry (MITI) has announced that it is working with industrial organizations to research photovoltaic conversion systems with the objective to develop SPS in the future. The organization conducted a survey mission to the U.S. including officers of MITI and industrial organizations from January 19 to February 2, 1992, "to exchange information on existing and emerging terrestrial and space solar technologies in order to investigate the feasibility of SPS." The Institute of Space and Astronautical Science has an ongoing R & D effort on technologies applicable to the SPS. For the past 10 years, it has held annual Space Energy Symposia on SPS-related technologies, and cooperates with Japanese industrial and academic organizations in planning near-term demonstrations of microwave beaming [29]. The SPS Working Group of ISAS is planning to launch a Minix sounding rocket to test the Microwave Experiment Transmission System in 1992 [30] as part of the International Space Year activities.

Japan's consideration of the SPS was started as part of the Sunshine Project in 1974 when it was listed as a long-range development objective. The participation of Sunshine Project representatives in SPS '91 in Paris and an official mission to the U.S. in January 1992 indicates the continuing interest in this option. Japanese industry has the ability to develop the microwave power beaming system for the SPS, and has potential access to launch systems to conduct various demonstration experiments as the technical, economic and societal issues are resolved, and the market for electrical power generation with an SPS system on a global scale is defined. The magnitude of this market projected to reach 5000 GW by mid-century is the largest single market on Earth, and would result in significant benefits for Japan's industry if the successful penetration of the consumer electronics, microwave oven, computer and automobiles would be extended to include SPS systems.

Former U.S.S.R.: The former U.S.S.R. space program officials have alluded to the connection between the MIR space station and the SPS. For example, deployment of a space antenna constructed by Aerospatiale was accomplished during extravehicular activities by French and Soviet cosmonauts in December 1989.

The U.S.S.R.'s interest in SPS is evident in the book edited by Professor V. S. Avduyevsky, Moscow Aviation Institute [31], who states: "The idea of satellite solar electric power stations generating energy for consumers in space and on the ground has grown into one of the most fundamental research programs." The Intercosmos Council, USSR Academy of Sciences, outlined a ten year development program for SPS and a space to Earth power beaming demonstration in 2010 [32].

The active participation of representatives of the Moscow Aviation Institute, State University of Moscow, Dniepropetrovsk University and University of Georgia in SPS 91, Paris is indicative of the continuing interest in SPS, and in participating in international endeavors associated with the development of a broad range of technologies and systems including launch services, and experiments on MIR and other spacecraft.

Development Strategy: There is a growing recognition by organizations interested in power beaming that the baseline technologies underlying the SPS concept can meet a number of near- and intermediate objectives. As Fig. 1 shows, these objectives are in line with evolutionary developments with definable economic values and societal benefits leading to macroengineering projects associated with power from space including power beaming from Earth orbits, from cislunar space to the moon and in the more distant future to other planets.

Evolutionary developments are being defined and include the following projects which are being investigated by organizations in several countries:

High altitude, long-endurance airplanes/platforms powered by electric motor driven propellers receiving microwaves beamed from Earth transmitters. Ap-

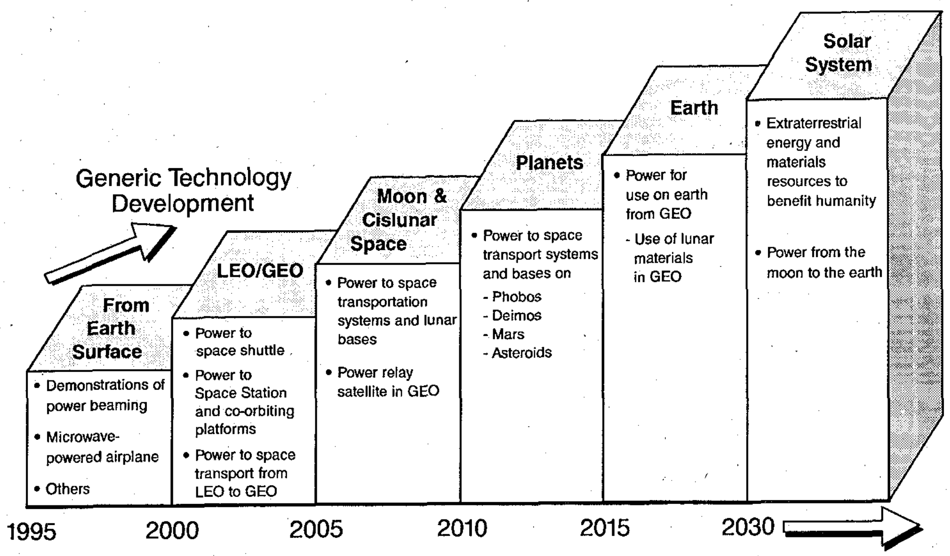

Fig. 1. Growth path for SPS development.

plications range from specific missions for Earth observations to communications. The feasibility of such applications was already demonstrated in the microwave-powered helicopters by Raytheon in 1962, and in 1987 by the Canadian Department of Communications with the Stationary High Altitude Relay Platform.

Power beaming on Earth to overcome natural obstacles or to mitigate ecological impacts that preclude the construction of conventional transmission lines. For example, beaming to remote, inaccessible settlements in Alaska [33], or across a mountain range on an island. The feasibility of supplying power ranging from 50 to several hundred kW across distances of several miles is being evaluated by a number of organizations in Europe, Japan and U.S. Power beaming was already successfully demonstrated in 1975 at Goldstone, CA, the site of NASA's deep-space technology tracking antennas, where 30 kW of microwaves were beamed across a distance of one mile, and converted into electricity with an average efficiency of 83% [34].

Power beaming on Earth across intercontinental distances from sites where renewable energy resources are available. The concept of wireless power transmission can be traced to Nikola Tesla [35], Herman Oberth [36], and Krafft Ehricke [37]. Renewable resources including wind, hydropower and photovoltaics can be developed in remote areas on several continents, e.g., hydropower in Alaska, and South America, wind in Alaska and Chile, and photovoltaics in desert regions of North Africa [38]. Typically, there are only limited markets for the power that could be generated at such sites of renewable energy resources.

Power beaming from Earth to space would supply power to a space station in an equatorial low-Earth orbit when beamed from several locations on the equator, and for electrical propulsion [39]. Beaming power from an orbiting power station to elements of the space infrastructure in low-Earth orbit, e.g., to maintain a space shuttle in orbit for an extended period, or to augment the power supply of a space station [40]. Microwaves at 35 GHz and higher frequencies, including laser frequencies, are more advantageous in space because absorption by the atmosphere is no longer a factor [41]. Microwaves at 35–38 GHz used in sunny regions may be only 1.5 to 2 times less effective than 2.45 GHz microwave beams [42].

Power beaming from Earth is potentially applicable to the requirements of future space missions in support of the Space Exploration Initiative. Power beaming in the laser portion of the electromagnetic spectrum for electric propulsion and to the lunar surface could be considered for these missions.

There is an emerging consensus about the utility of power beaming. The preceding plans for demonstration projects of power beaming to be accomplished during the next decade are expected to provide valuable data applicable to technology development, and economic and societal assessments of SPS.

Progress in the Future

The SPS reference system that was the basis for assessments by NASA, U.S. Department of Energy, National Research Council and the Office of Technology Assessment no longer represents the current and projected state-of-the-art of space power. There is a growing recognition that space programs, systems and technologies being developed in several countries are advancing the feasibility of the SPS. For example, the attainment at the Boeing High Technology Center, Seattle, WA, of high concentration, 31% efficient gallium arsenide solar cells, (AM-O); a projected 42% (AM-1) two sided cell being developed by the Ioffe Institute, St. Petersburg; demonstration of laser performance and development of microwave power transmission in the SDI program; single stage to orbit launchers capable of takeoff and landing, with airline type ground operations support to reduce launch costs; automated EVA retrievers in support of the Space Station assembly; and the planning for a lunar base and a manned mission to Mars, including beaming power to lunar and Martian surface sites. It is possible now to project trends in technologies critical for SPS applications and to establish technology development goals envisaged for a global SPS system. Meeting these goals can achieve the vision of the National Commission on Space [43]: "Our ambition: Opening new resources to benefit humanity."

An evolutionary development of the SPS concept to meet intermediate objectives with definable benefits is the most likely scenario for SPS development. The SPS represents a fertile field for innovations. Few of the potentially interesting alternative technologies have been analyzed in sufficient detail. It would be premature to choose from among them because the consequences of these technologies cannot be evaluated without a vigorous system study of the impact of advanced technologies on SPS designs at the system and subsystem levels, based on information obtained from demonstration projects.

The implicit assumption in the U.S. Department of Energy and NASA program was that the SPS is a project requiring a massive commitment of funds over the next several decades. An approach can be devised for the development of the SPS that identifies the underlying generic technologies and their application to specific intermediate projects, as shown in Fig. 1. The "terracing" of such projects would reduce the challenges typically associated with large-scale projects, including the control of the project, the effects of technical uncertainties, maintenance of investor confidence, reduction of environmental impacts, and the difficulties associated with termination of the project, if warranted. The increasing capabilities needed for already planned space projects will contribute to the industrial infrastructure that could be the foundation for SPS development.

Projects such as the SPS are unlikely to be pursued until information from other projects at successive "terrace" levels can guide the evolution of the most appropriate design for the SPS. The assumption underlying the "terracing" approach is that advanced technologies will be developed in support of existing or planned national and international space projects.

This approach will be judged successful when technical uncertainties and risks in the SPS program are greatly reduced, the industrial infrastructure is established, and substantial information is available on the technical feasibility, economic viability, and societal and environmental acceptability of the SPS designs to decision-makers. SPS development will occur within the context of the evolving space industrial infrastructure that will be essential for space commerce and in consonance with the political and economic interests and actions of governments, and in accordance with international laws.

Conclusion

The challenges to develop a global SPS system capable of using terrestrial and lunar resources are formidable. International efforts will be required over a period of decades to make the transition from the current to 21st Century energy production methods to power beamed from space to Earth. Efforts that already were underway in Europe, Japan, U.S. and the former U.S.S.R. are a promising beginning in the face of the gravity of the potential distributions associated with global population growth and ecological deterioration.

As a result of these efforts the following conclusions can be arrived at:

- Lunar resources including metals, glasses and oxygen promise to provide commodity materials for the construction of the SPS in geosynchronous orbit.
- Technology advances, performance improvements and projected cost reductions in solar cell arrays, large space structures, laser power transmission, microwave generators and rectifiers, and space transportation system increase the technical feasibility and economic viability of the SPS concept.
- The significant progress that has been made as a result of broadly based technical, economic, environmental and societal studies on the SPS is resulting in a growing consensus that the SPS is one of the few promising power generation options that could contribute to meeting global energy demands in the 21st Century.
- The SPS concept has the potential, not only for base-load power generation on a global scale, but also represents an evolutionary direction for expanding human activities in space and the use of extraterrestrial materials.
- The expansion of the space industrial infrastructure is a strategic goal for a growing number of countries because space activities are seen as the key to future economic growth and international influence.

There is a long road ahead before there will be certainty about the destiny of the human species as it evolves beyond the surface of the Earth. As Arthur C. Clarke pointed out: "Our ability to understand what we can do in space is about equal to that of a fish imagining fire."

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