N90-10144

S4-20

216768

POWER FROM SPACE FOR USE ON EARTH: AN EMERGING GLOBAL OPTION

LW 086419

Peter E. Glaser
Vice President
Arthur D. Little, Inc.
Cambridge, Massachusetts, U.S.A.

Abstract

The concept of the Earth as a closed ecological system is addressed from the point of view of the availability and use of energy from space and its potential influence on the economies of both developed and developing countries. The results of past studies of the solar power satellite (SPS) are reviewed, and the current international activities exploring various aspects of an SPS are mentioned.

The functions of an SPS, including collection of solar energy in orbit, conversion to an intermediate form of energy, transmission of energy from orbit to Earth, and conversion to useful energy in the most appropriate form, are discussed, and directions for future developments are indicated, including a suggested planning framework.

Salient aspects of SPS technologies are presented, and the potential benefits of the uses of lunar materials for the SPS construction are outlined. Scenarios within the context of international participation in a global SPS system are presented.

The conclusion is drawn that an SPS system is one of the few promising, globally applicable power generation options that has the potential to meet energy demands in the 21st Century and to achieve the inevitable transition to inexhaustible and renewable energy sources.

Introduction

The time horizon for the development of energy technologies that may be the key to meeting future global energy need encompasses a period well beyond 2000. Although there is no dearth of projections on how these energy needs may be met, the dynamic changes taking place in the scientific and technical fields, the increasing role of developing countries on the international scene, and the mounting threats of present energy resource utilization to the Earth's ecology, e.g. global warming, require that all worthwhile options for energy production be explored. To achieve the inevitable transition to inexhaustible and renewable resources, the potential of power generated in space for use on Earth is receiving renewed attention.

A major study of space power was performed over a decade ago by the U.S. Department of Energy and NASA (1). Its participants concluded that solar energy converted in space and beamed to Earth via laser or microwaves was technically feasible, and they could not identify any insurmountable economic or environmental obstacles.

The rationale for a transition to new energy sources is presented in the light of current information on energy projections. Advances in technology and economic considerations of their significance to space power applications provide a new dimension to the expansion of the space infrastructure and the opening of new resources beyond the surface of the Earth that could benefit all humanity.

Background

Technological advances during the 20th Century in all fields of human endeavors have occurred at a dizzying pace. Within one lifetime, events of such significance have occurred that it is hard to grasp their implications when considered in isolation. Seemingly there is a discontinuity in societal development with consequences that were unthinkable at the beginning of this century. This generation of scientists has shed the shackles of gravity and explored the outer reaches of the solar system, unlocked the forces within the atom, and devised methods of electronic communication that have created the "global village". The threads of life have been recombined and the uniqueness of planet Earth has entered human consciousness. The illusion that man has unlimited capabilities to control nature and fashion the environment based on scientific understanding and technological prowess has engendered a naive belief that man can control nature and exploit energy and material resources with impunity to meet his immediate needs. Only scant regard is paid to the reality that these resources are irreplaceable assets, and that their profligate use may threaten the global environment and even the conditions under which future generations may have to live.

Future Global Energy Demands

One of the major challenges facing contemporary society is the development of technologies that will meet future global energy demands. Even if one assumes that energy efficiency improvements and energy-conserving paths are being pursued with all possible vigor, and that economic success and well-being is no longer measured only by per capita energy consumption, the trend in electrical power demand growth to meet global economic advancement will continue, e.g., in the United States at a rate of 2.6 percent per year to the year 2000 (2). Projections of electric demand tend to underestimate the actual increase in electric end-use intensity, because the increased demand will be in response to uses of advanced process equipment that ranges from microwave ovens, computer-driven operations, and communication systems to electric arc furnaces for steel-making and semiconductor production processes.

Electric demand in developing countries will increase during the next decades at a much greater rate than in developed countries. The availability of adequate supplies of electricity, along with technical advances, will be required to achieve the economic growth desired and to meet the unfulfilled expectations of growing populations of these countries. Currently U.S. per capita annual energy use runs about 10,000 kWh, as compared to 250-370 kWh in lower-income developing countries (3). This enormous disparity in energy consumption will effect a greatly increased demand for electricity in developing countries--one that is projected to increase at an annual demand growth of 7 percent and even higher in countries that are industrializing rapidly.

The lag in improvements in electricity generation and distribution infrastructure results in demands that far outstrip supply. They range from 10 percent in India to 25 percent in Pakistan. If developing countries were to industrialize with an energy intensity that approached that of the developed countries, an unsustainable five-fold increase in world energy demand is projected (4).

Transition to New Energy Sources

To meet the global energy demands of the civilization of planet Earth in the 21st Century, transition to an energy economy that is based on inexhaustible and renewable energy sources will have to be made. Fusion and solar energy are the major options that, in suitable combinations, may be able to sustain the energy requirements of an interdependent global energy economy. Although fusion is a potential option, a practical controlled fusion reactor has yet to be demonstrated. The conversion of solar energy for a wide range of distributed and centralized applications can provide nearly unlimited amounts of energy to meet all conceivable future global needs.

There are two primary approaches to the conversion of solar energy :

1. Terrestrial solar energy conversion technologies, such as water heaters, passive heating, industrial process heat, biomass, photovoltaics, solar dynamic, wind, and hydroelectric generation. Except for hydro-electric generation, the conversion of solar energy into electricity requires suitable energy storage methods to compensate for diurnal and seasonal variations in insolation and interruptions of solar rays by unfavorable weather conditions. Energy storage not only reduces the efficiency of the conversion process, but it also contributes to system costs, especially if large-scale or base-load (continuous) conversion systems are required.

2. Solar energy conversion in space for use on Earth, was proposed in 1968 (5) to overcome the drawbacks of terrestrial solar energy conversion systems for the generation of base-load electricity, and is being increasingly considered by several countries.

The Solar Power Satellite (SPS) Concept

The proposal for an SPS was motivated by the following considerations:

The average solar ratio (SR) for the land areas of the Earth, that is, the ratio of total solar insolation for a year on a given area to the total energy use in that area, is currently about 3,000 and will decrease as world energy consumption rises. For the industrialized countries, the mean SR is about 80. These low SR values mean that industrialized countries, even if the highest conversion efficiencies conceivable were assumed, could not obtain more than a small part of their energy needs from the sun unless highly-efficient and moderate-cost systems are available to transport energy from the sunny under-populated area of the world or from high-Earth orbit locations, e.g.: geosynchronous orbit (GEO), where solar energy is consistent and available except for very short-term and precisely predictable interruptions during eclipses around equinoxes.

The SPS concept can meet the requirements for base-load electricity of both developed and developing countries, providing a wide range of design options with generation capacities ranging from a few 100 MW to 5 GW or more.

When an SPS is located in GEO, 36,000 km above the equator, the insolation level -- 1.35 kW/m^2 - is higher than it is at the Earth's surface and it is constant during the year (except during very short eclipse periods). In this orbit, the solar energy collected can be converted into electricity and transmitted to Earth locations via a microwave or laser beam, -- where it can be converted back to electricity. A microwave-receiving antenna on Earth was demonstrated at Goldstone, CA, to have an efficiency of 82 percent in 1975. A microwave beam would suffer an attenuation of only a few percent as it passed through the Earth's atmosphere, even under unfavorable weather conditions.

The annual capacity factor of an SPS would be nearly 100 percent (compared with 20-30 percent for most terrestrial solar power plants without energy storage.) The SPS would be a continuous source of renewable energy, and there would be only limited siting constraints for receiving antennas either on land or in the oceans. Even a very large-area SPS in GEO, such as a 5-GW SPS, would not cast a shadow on the Earth because its angular size is much less than that of the Sun.

SPS Technical Features

As originally conceived, an SPS could utilize various approaches to the conversion of solar energy, such as photovoltaic and solar dynamic. 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. An added incentive was the substantial progress being made in the development of advanced photovoltaic materials and the increasing confidence in the achievement of significant cost reductions.

High-efficiency solar cells are being developed. Both single- and multiple-band gap solar cells are being used for solar concentrators and flat solar arrays, and they are exhibiting increased resistance to the space radiation environment. In the development of space solar cells, at first scientists relied on single-crystal silicon, the mainstay of current satellite power systems. Silicon solar cells presently achieve efficiencies in the 15 percent range and show a power density of about 50 W/kg. A significant increase in both range and power density can be achieved when concentrator arrays are used. Gallium arsenide solar cells have already been developed for use with light-weight concentrators. With small attitude corrections, they will always face the sun. Advanced photovoltaic materials, such as gallium arsenide and indium phosphide, will most likely supercede silicon cells for use in space. Gallium arsenide solar cells have achieved a demonstrated efficiency of about 24 percent, while indium phosphide has reached a 19 percent level and attained a specific power density of 100 W/kg with a solar concentrator.

Solar dynamic conversion has been considered as an alternative to photovoltaic conversion because conversion efficiencies with this technology are expected to be higher than those achieved with solar cells developed earlier. Solar dynamic conversion, although promising, has not yet been demonstrated in space applications, but it is currently being considered for use in powerplants in space in both low- and high- Earth orbits.

The area of a solar collector required for energy conversion by the SPS is about one sixth to one third the area of a collector located on Earth at a comparable conversion efficiency. When a microwave beam is used, the diameter of the receiving antenna is a function of the diameter of the transmitting antenna, the wavelength used, and the distance between the two antennas. For example, to provide 5 GW of power on Earth to a transmission grid would require a receiving antenna that was about 8 km in diameter. If an infrared laser were used, the receiving site would be less than 1 km in diameter; however, the transmission efficiency in unfavorable weather would decrease.

The launch costs to low-Earth orbit (LEO) fall in the \$2,000-\$4,000 per kg range when using either expendable launch vehicles or a space shuttle: LEO-to-GEO transportation of major SPS components assembled at a LEO space station can be accomplished with solar electric propulsion (ion thrusters). About 80 percent of the transportation costs are for transportation from Earth to LEO.

Although advanced launch systems using chemical fuels are expected to reduce transportation costs, it is unlikely that they will approach the goal of about \$100 per kg in the foreseeable future. Most of the materials that would be required for constructing an SPS are commodity materials; therefore, obtaining as much as 60 to 90 percent of such materials from the moon is being seriously considered because transportation costs are expected to be reduced by about an order of magnitude, and the Moon's gravity is but a sixth that of the Earth.(6)

SPS Economic Considerations

The objective of the SPS is to generate base-load electricity for use on Earth. Economic justification for SPS development must acknowledge that it is not possible to know now the cost of a technology that will not be developed for at least 10 years, or commercialized in less than 20 years. The decision regarding development of an SPS will depend on the global demand for electricity, the timing for the commercialization of a SPS in competition with other alternative energy technologies, the limits placed on the use of fuels that contribute to the atmospheric warming trend, and the stage of development of the space infrastructure.

An SPS reference system design developed by NASA and the U.S. Department of Energy in the late 1970s (1) would deliver 5 GW of power to the Earth using a 1.6-km diameter transmitting antenna in an SPS and a 8-km diameter receiving antenna on Earth. A rough estimate of the cost of a complete SPS system is \$3,000-5000 per kW.

Although it is very difficult to project costs per kW for an SPS at the concept development stage, a number of developments tend to make this project more feasible today. They include: buildup of the space infrastructure consisting of space transportation systems, space stations, and platforms, thin film and high-concentration solar cells, solar dynamic conversion, large space structures, automated assembly, high frequency microwave transmission and advanced lasers. Furthermore, funding for space activities by several countries, which globally is approaching \$50 billion per year, is increasing. Specifically, Europe, Japan and the Soviet Union are planning significant programs with the objective of developing space power systems during the next 30 years.

The significance of space power development was recognized at the planning conference for the International Space Year (ISY). An international space power test program was recommended for performance within the framework of the ISY with the objectives: "to evaluate the feasibility of collecting and converting solar energy, and transmitting energy at levels necessary to facilitate industrial applications in orbit or on Earth." (7)

Applications of SPS in Developing Countries

An SPS could be of particular interest to those developing countries that lack conventional energy sources. They could bypass the 'smoke stack' era that characterized energy development following the industrial revolution, while providing for their own specific growing energy needs. Laser beams transmitting about 100 to 500 MW of power from space to selected sites on Earth would be attractive because smaller additions to power-generating capacity could be more easily integrated in an evolving transmission grid as compared with a 1- to 5-GW SPS using a microwave beam.

An SPS can be designed that will beam power to more than one receiving site to meet peak energy needs in several time zones to supplement terrestrial electricity generation capacity. An SPS system consisting of a number of satellites with different outputs and capacities can be organized to take into account technical, economic, and societal issues and be capable of meeting the needs of both developing and developed countries. The Intelsat organizational structure has already been successful in operating a global communication satellite system, and has been a model for the International Maritime Satellite (Inmarsat) organization. Proceeding with a U.S. effort akin to Comsat, leading to the creation of an international organization for developing and operating a global SPS system may achieve "international cooperation in an area of high national stakes and strongly-held differences in views"(8), can be a means to maintain significant U.S. industry involvement.

SPS Growth Path

An implicit assumption in any large-scale project is that the decision-making process is fraught with uncertainties associated with projected system performance, costs, and environmental effects. Furthermore, the need for the continuing support of public and private investors over an extended time period is also required. This was the case with NASA's Apollo program that was conceived and executed with a definite start date and agreed-upon performance objectives, budgets, and schedules, and with an identifiable management structure that was made responsible for landing man on the moon. That is to say, it was a "monolithic" project. The time needed to complete such projects makes them vulnerable to changes in the regulatory environment, and if they should extend over a decade or more, they become vulnerable to changing economic and political conditions as well. A continuing consensus of both public and private investors, as well as the support of appropriate interest groups and government agencies, is required until the project is completed.

An approach can be followed in the development of the SPS that identifies essential generic technologies, pursues intermediate applications of these technologies with near-term returns on investment, e.g., space power for use in space shuttles, space stations, free-flying platforms, electric propulsion lunar and planetary bases, and on Earth. This "terracing" approach to large space projects (9) can reduce the risks associated with a "monolithic" project. As part of this approach, essential generic technologies will have been demonstrated in other applications, that are justified on their intrinsic economic benefits. The growing generic technology data base can then be incorporated into the ongoing SPS planning and R&D efforts. Figure 1 shows a power beaming growth path with intermediate objectives designed to support "Our Ambition: Opening New Resources to Benefit Humanity" (10).

In parallel, assessments of economic, regulatory, legal and societal issues will influence decisions that pertain to the growth path for the SPS, leading to a broad consensus with respect to the overall technical, economic, and political feasibility within the framework of international activities that pertain to the implementation of a global SPS system.

The commercialization of space power -- at first for use in space and subsequently for use on Earth -- will permit participating organizations to obtain returns on investments without a long-term commitment to a global SPS system implementation.

An SPS has the characteristics of an ideal space enterprise. Such an enterprise "would have a stable, predictable, very large market on Earth and, once established, would not be dependent on Earth-to-orbit transportation costs to generate continuing revenues" (11).

Conclusions

The expansion of the space infrastructure is a strategic goal for an increasing number of countries that are expanding their technological capabilities to participate in commercial space activities. These activities are increasingly being recognized as the key to future economic growth, industrial expansion, and space market penetration. The commercial potential of space markets is so large that space industry endeavors could be among the fastest growing and important industrial activities in the 21st Century.

The development of space power can provide a critical dimension to the growing efforts of mankind to move beyond the surface of the Earth and to benefit from the limitless energy and materials resources of the solar system. Now is the time for taking a positive view of the achievable economic returns from space endeavors. There is little doubt that the future uses of space resources will have the most profound effects on the civilization of planet Earth and that new knowledge, increased understanding, and enhanced scientific and technical capabilities will be essential to confront the challenges that must be overcome to achieve the inevitable transition to inexhaustible and renewable energy resources. Moving towards this goal, a truly global civilization that will benefit all humanity may be created.

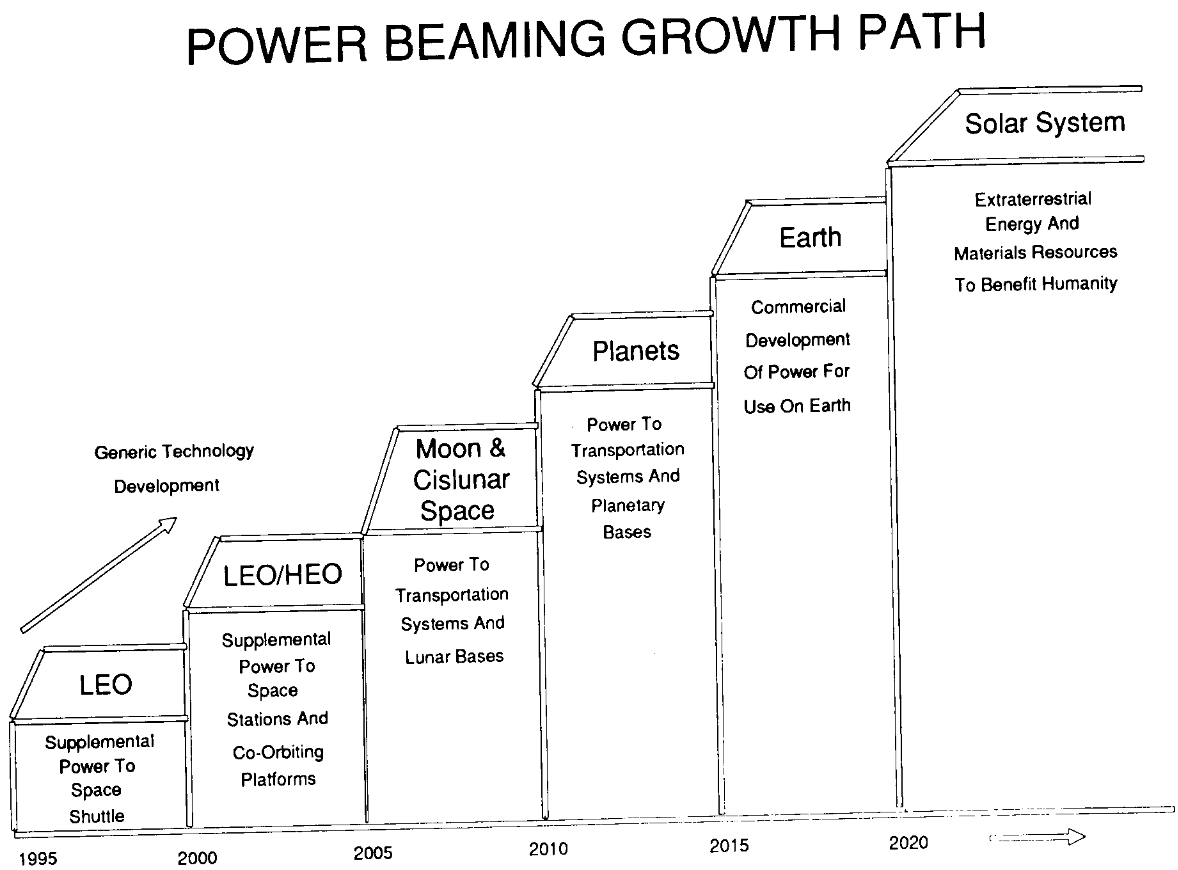
POWER BEAMING GROWTH PATH
Solar System
Extraterrestrial Energy And Materials Resources To Benefit Humanity
Earth
Commercial Development Of Power For Use On Earth
Planets
Power To Transportation Systems And Planetary Bases
Moon & Cislunar Space
Power To Transportation Systems And Lunar Bases
LEO/HEO
Supplemental Power To Space Stations And Co-Orbiting Platforms
LEO
Supplemental Power To Space Shuttle
Generic Technology Development
1995
2000
2005
2010
2015
2020

Figure 1

REFERENCES

1. U.S. Department of Energy, Satellite Power System Concept Development and Evaluation Program System Definition Technical Assessment Report, DOE/ER/10035-03, Dec. 1980, NTIS, Springfield, VA 22161.

2. U.S. Department of Energy, Annual Outlook for U.S. Electric Power 1987, Projections through 2000, DOE/EIA-0474(87), Energy Information Administration, Washington, DC, 1987, p.8.

3. H.C. Bailly, "U.S. Energy Association Seminar on the Third World Power Crisis," presented in Washington, D.C., February 1968.

4. Ibid.

5. P.E. Glaser, "Power from the Sun: Its Future", Science, Vol. 162, 1968, p. 857-886.

6. P. Du Bose, "Solar Power Satellite Built of Lunar Materials", Space Power, Vol. 6, 1986, pp. 1-98.

7. Report on the Pacific ISY Conference, August 19-21, 1987, Kona, Hawaii,--Th. B. McCord, editor, University of Hawaii at Manoa, Hawaii Institute of Geophysics, February 1988.

8. J.M. Logsdon, "Solar Power Satellites: The Institutional Challenge", Space Power, Vol. 4, 1983, p. 26.

9. P.E. Glaser, "The Solar Power Satellite -- A Goal for the Economic Development of Space", Space Power, Vol. 5, pp. 83-90, 1985.

10. National Commission on Space, Pioneering the Space Frontier, Bantam Books, Inc., New York, May 1986, p. 3.

11. Ibid., p. 82.