Satellite power stations: a new source of energy?

Solar cell power, converted to microwave power, is beamed to earth and reconverted

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The rapidly increasing demand for electric energy[1,2] —coupled with the inability of conventional means of electric power generation to keep up with that demand—makes urgent the need for new prime energy sources for future electric power generation. In addition to nuclear fuels, there are many potential sources of energy that are not now being used in appreciable amounts: wind and tidal energy, geothermal energy, temperature differences in the ocean, and solar energy. This article will be concerned with solar energy.

For each possible energy source, including nuclear fission and fusion, there is some factor that limits the degree of optimism. Either the source is too small to qualify as a major energy source, hard-to-assess pollution and ecological hazards are unavoidable, the technology has not yet been reduced to practice, or there is an economy barrier. Solar energy falls into the last category.

The amount of solar energy intercepted by the earth is at least 10 000 times the projected consumption of electric energy in the year 2000. Because the sun's energy has such a low density at the earth's surface, any earth-bound power generation scheme based on the sun as energy source would require relatively large areas devoted to devices that either convert the sun's energy directly into electricity or function as boilers for a system employing turbogenerators. Moreover, the day-night cycle, atmospheric attenuation, cloud coverage, and other factors reduce the amount of solar energy falling on a given location to a small fraction of that falling on the same area in space. In December, for example, the sunniest locations in the United States, located in the Southwest and in Florida, receive only 11 percent of the energy that a similar area in space would receive.[3] In New York and Seattle, by contrast, the percentages would be 4.5 and 2.2 respectively. The impractical result of these poor duty cycles is an excessive investment in solar energy devices[4] to capture a given amount of energy. And an equally excessive investment in storage facilities must be made if the captured energy is to be used as a reliable base-load source of electric power.

To overcome the problems resulting from this poor duty cycle, Dr. Peter Glaser of Arthur D. Little, Inc., proposed, in 1968, that we put large arrays of solar photovoltaic cells into space in near-equatorial synchronous orbit where the sun would shine upon them nearly 100 percent of the time.[5] The dc power obtained from the photovoltaic arrays would then be converted into microwave power, beamed to the surface of the earth, and there converted back into dc power. Because the rotation of the solar satellite would be synchronous with that of the earth, the microwave link would be fixed and operative at all times. This concept has become known as the Satellite Solar Power Station (SSPS).

Dr. Glaser's proposal was received with considerable interest because of the concept's inherently low thermal pollution; because of the absence of any form of particulate, chemical, or nuclear pollution; and because of its association with a dependable, inexhaustible source of energy—the sun. This interest has led to a series of studies of the technology and associated economics of the system in stages of increasing depth.[5–7] The latest study was performed by a four-company team, with Dr. Glaser as its leader, consisting of personnel from A. D. Little, Inc., the Grumman Aerospace Corp., Raytheon Co., and Textron, Inc.

After a six-month study of all aspects of the SSPS, the team reached the conclusion that the satellite solar power station concept, as proposed by Dr. Glaser, is technically feasible.[7,8] The present cost projection —based upon solar cell costs derived from an automated version of today's conventional silicon solar-cell technology and upon space transportation costs as represented by a first-generation space shuttle—is too high to be cost competitive with established methods of power generation. Because of the 15 to 25 years projected time frame for the SSPS to become operational, it is entirely possible that breakthroughs in cost will occur.

A preferred way to view the SSPS system concept is that it is a pollution-free, resource-conserving approach to the solution of our energy problem in the time frame 1990–2000 and that it is based upon an inexhaustible prime energy source, our sun. Although not currently cost competitive, it is an option that should be considered carefully and kept open in the event cost breakthroughs occur and unexpectedly severe problems arise in the development of other approaches.

System configuration and characteristics

The overall configuration and principal characteristics of the SSPS to be presented make up a "baseline" design.[7] It is not intended as a final design but rather to serve as a starting point for further study and the evolution of improved designs.

The system is shown on the front cover of this issue. The SSPS is placed in an equatorial, synchronous geocentric orbit 35 800 km above the earth's equator so that its position with respect to any other position on the earth's surface is fixed. Two large solar photovoltaic cell arrays, always pointed toward the sun, convert the sun's radiant energy to dc power, which is then transferred to a large, active phased array mounted by means of two rotary joints between the two solar arrays. The active phased arrays' functions are to convert the dc power into microwave energy at a preferred wavelength that will penetrate the earth's atmosphere and to focus that energy into a narrow beam pointed toward the receiving point on the earth's surface.

The microwave beam in space is unattenuated and arrives at the earth's atmosphere with the same power level as at launch. The microwave energy then penetrates the earth's atmosphere and reaches the earth's surface where it is efficiently converted back into dc power by a device known as a "rectenna," which simultaneously absorbs and rectifies the incoming microwave energy.

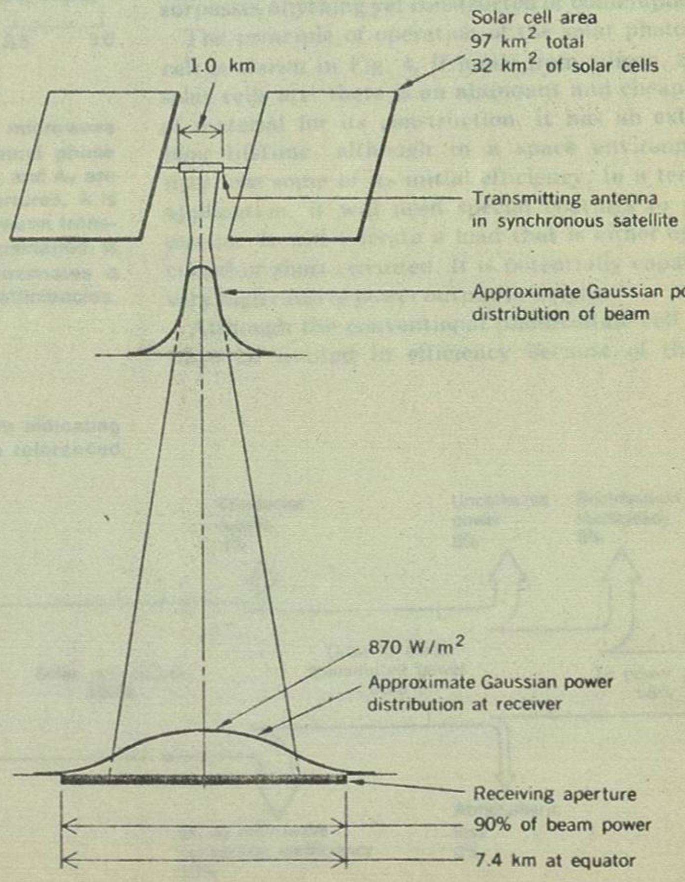
An important characteristic of the SSPS system is its high duty cycle. Because of the 23-degree tilt of the earth's axis with respect to the ecliptic plane, and the fact that the satellite is at a distance of 35 800 km (22 400 miles) from the earth in equatorial orbit, the SSPS is continuously illuminated during the winter and summer months and well into the spring and fall months. For 22 days before and after the vernal and autumnal equinoxes the satellite is eclipsed for periods of time ranging up to a maximum of one hour and 14 minutes. If the satellite and ground rectenna are located at the same longitude, the eclipse period will center around midnight. The average duty cycle for the entire year is slightly more than 99 percent.

The proposed electrical size of a single SSPS is in the range of 3000 to 15 000 MW. To place this power level in perspective, 10 000 MW represents about 3 percent of the electric generating capacity in the United States today but only 0.5 percent of the projected capability in the year 2000. The electrical size of the system is determined primarily by the power level at which the construction cost per kilowatt of output is at a minimum. Although many parameters are involved, the most important ones appear to be the area of the transmitting antenna aperture required for efficient transmission of power, the most efficient utilization of this area for radiation of waste heat, and the bus losses associated with the transmission of dc power from the solar cell array to the transmitting antenna.

The choice of frequency for the microwave transmission of power, from a strictly technological point of view, involves several factors: how the attenuation and scattering of electromagnetic energy in the earth's atmosphere behave as a function of the wavelength of the energy; the physical size of the transmitting antenna and receiving rectenna; and the efficiency of the components that interchange dc and microwave energy. A study of atmospheric attenuation versus wavelength shows that a wavelength of 7.5 cm (4 GHz) or longer is necessary to avoid excessive attenuation (>1 dB) during a heavy rainstorm, the form of atmospheric disturbance having greatest impact upon microwave propagation. Atmospheric scattering and attenuation effects become much more pronounced at millimeter and optical wavelengths and prevent serious consideration of this part of the spectrum for efficient power transmission.

From the viewpoint of keeping aperture sizes small, a short wavelength is preferred since the total area of the two apertures is proportional to wavelength for a given efficiency. However, substantial aperture areas are necessary for disposal of any waste heat resulting from any inefficiencies in energy conversion, particularly in space. Energy conversion components presently have better efficiency at the longer wavelengths.

[1] Dimensions of essential physical features of the SSPS for a 10 000-MW system.



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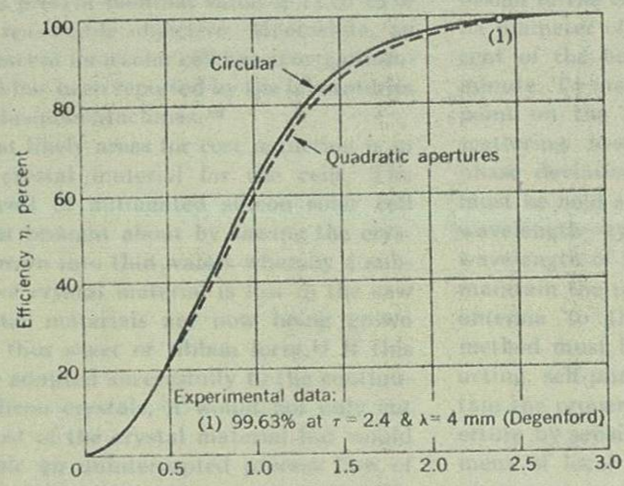
The net result of these considerations is that at the present time, and from a strictly technological point of view, the best compromise appears to be in the relatively narrow range of 7.5 to 15 cm. In the SSPS design, a wavelength of 10 cm has been assumed.

The proposed physical size of the present base-line design is shown in Fig. 1 for a 10 000-MW system. The solar energy collecting array has an area of 97 km^2; one third of that area is made up of solar cells and the remaining area consists of inexpensive solar concentrators made from thin-film material treated to have a reflecting surface. The transmitting antenna is 1 km in diameter, and the rectenna array to capture 90 percent of the transmitted energy is 7.44 km in diameter. The antenna dimensions are derived from the relationship between efficiency and physical parameters given in Fig. 2.



[2] Theoretical transmission efficiency for a microwave beam radiated from an aperture with a spherical phase front whose radius is equal to the distance D. A_t and A_r are the areas of the transmitting and receiving apertures, λ is radiation wavelength, and D is the distance between transmitting and receiving apertures. Aperture illumination is unique for each value of efficiency but approximates a slightly truncated Gaussian distribution for high efficiencies. One point of experimental data is given.

The overall efficiency of the SSPS system is the product of the efficiency of the solar cell array and the microwave power transmission system. The solar cell conversion efficiency is limited, primarily because of the distribution of the sun's energy over a very broad frequency spectrum. The conversion efficiency of today's silicon solar cells is in the range of 12 percent. It is expected to improve to 18 percent[9] but never to exceed 25 percent. The use of concentrators reduces the cost and weight of the array but the resulting higher temperature of the cell also reduces the projected efficiency of the solar cell to 11.5 percent.[7]

By contrast, the overall efficiency of the microwave power transmission system is projected to be in the 65 to 70 percent range. Figure 3 shows the various power flows and losses in the SSPS system using the dc power input to the active phased array as the 100 percent reference point.

The specific weight of the satellite portion of the SSPS system, important because of space transportation costs, has been estimated to be 2.5 kg/kW of output.[7] More than half of this weight is associated with the solar cell array.

The satellite solar power station would be placed into orbit with the space shuttle[7] or perhaps a second-generation shuttle that would transport material from the earth's surface to near-earth orbit and a space tug utilizing high-specific-impulse electric propulsion to go from near-earth to synchronous orbit.

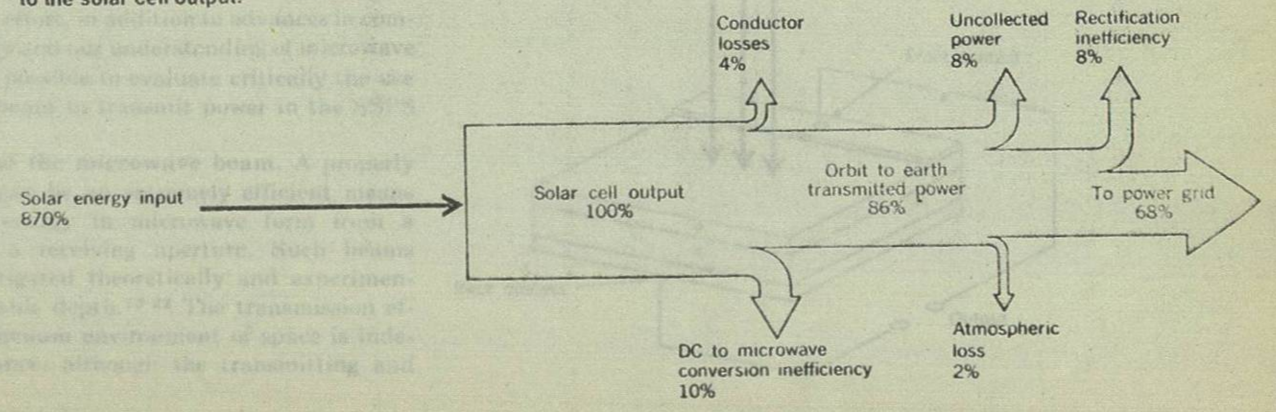
Solar photovoltaic cell array

In the SSPS the sun's energy is converted into electric power by a large photovoltaic array optimized for this purpose. Its design uses construction techniques extrapolated from present practices but the scale far surpasses anything yet constructed or contemplated.

The principle of operation of the solar photovoltaic cell is shown in Fig. 4. If made from silicon, as most solar cells are, there is an abundant and cheap source of material for its construction. It has an extremely long lifetime, although in a space environment it may lose some of its initial efficiency. In a terrestrial application, it will need special coatings to prevent erosion. It will tolerate a load that is either open-circuited or short-circuited. It is potentially capable of a very high ratio of power output to weight.

Although the conventional photovoltaic cell will always be limited in efficiency because of the sun's

[3] Projected flow of power in the SSPS system indicating various losses. The power flows and losses are referenced to the solar cell output.



broad spectrum of energy, an efficiency of 18 percent reportedly achieved with a cell based on gallium arsenide[10] represents about half the efficiency of conventional or nuclear generating plants using fossil or nuclear fuels. Solar cells also have the advantages that their prime source of energy, the sun, is inexhaustible and cost-free and that there are no residual wastes to dispose of.

The solar cell, in spite of its advantages, has not moved into serious contention as a source of large amounts of electric power because of its relatively high cost and poor duty cycle when terrestrially based. In space, however, it has been used widely and now represents the major source of power for satellites that are required to operate reliably for long periods.

As the result of the growing concern over future energy sources, there has been a renewed interest in improving the solar photovoltaic cell in terms of efficiency and reduced manufacturing cost. A recent study sponsored by the National Academy of Sciences[9] has indicated that an increase in efficiency of the silicon solar cell from its present nominal value of 12 to 18 or 20 percent is a reasonable objective. Meanwhile, an efficiency of 18 percent for a solar cell based on gallium-arsenide material has been reported by the laboratories of International Business Machines.[10]

One of the most likely areas for cost reduction is in growing silicon crystal material for the cells. The chief projected cost of automated silicon solar cell production is that brought about by sawing the crystal material as grown into thin wafers whereby a substantial amount of crystal material is lost in the saw kerf. Some crystal materials are now being grown commercially in thin sheet or ribbon form.[11] If this method could be adapted successfully to the continuous growth of silicon crystals, it would not only cut drastically the cost of the crystal material but would also make possible an uninterrupted process flow of the silicon material from the molten state to the finished silicon solar cell.[12] A resultant cost of $375 per kilowatt has been projected from a study[13] based upon an assumed successful adaptation of the ribbon process to silicon solar cells.

Microwave power transmission system

The proposed use[5,14] of a microwave beam for efficient transfer of large amounts of power over long distances is a radical departure from the traditional use of microwaves in radar and communications. A considerable amount of effort in the experimental development of microwave power transmission systems has been supported by private and Government agencies[15-18] and this effort, in addition to advances in component technology and our understanding of microwave beams, makes it possible to evaluate critically the use of a microwave beam to transmit power in the SSPS system.

The forming of the microwave beam. A properly launched beam can be an extremely efficient means of transporting energy in microwave form from a transmitting to a receiving aperture. Such beams have been investigated theoretically and experimentally in considerable depth.[19-22] The transmission efficiency in the vacuum environment of space is independent of distance, although the transmitting and aperture areas must increase in proportion to the distance. The relationship between efficiency η, transmitting and receiving apertures A_t and A_r, transmission distance D, and the wavelength λ of the radiation is shown in Fig. 2.[19] One experimental data point of 99.6 percent[22] is shown in Fig. 2.

The application of Fig. 2 to the problem of transferring power from a synchronous satellite over a distance of 35 800 km using a radiation wavelength of 10 cm shows that for 90 percent power transfer efficiency the product of the receiving and transmitting apertures must be 34.1 km^4. If the transmitting aperture is 1 km in diameter, then the receiving aperture will be 7.44 km in diameter, as shown in Fig. 1. The relationship provided by Fig. 2 requires that for each value of efficiency there must be a specific distribution of illumination at the transmitting antenna. For high efficiency values, this illumination approaches a slightly truncated Gaussian.

The gain of the transmitting antenna will be very high, of the order of 90 dB for the present base-line design of the SSPS transmitter. The proposed rectenna diameter of 7.44 km required to intercept 90 percent of the beam represents an arc segment of 0.7 minute. To maintain a given spot size around a given point on the earth's surface, and to maintain low scattering losses from the transmitting antenna, phase deviations over the phase front of the beam must be held at launch to within a small fraction of a wavelength—typically within 5 mm for a transmitted wavelength of 10 cm. Since it would be impossible to maintain the physical alignment of the surface of the antenna to this tolerance, some beam launching method must be employed that uses one of the fast-acting, self-phasing concepts.[23] These methods maintain the proper phase over the entire transmitting aperture by sensing electronically the physical displacement of local areas and compensating for any displacement by changing the phase of the microwave radiation at the point of launch. To be effective in the

[4] Salient features of standard solar cell. Basic material is single-crystal, n-type silicon. Thin layer of p-type material is formed on one surface. Enough energy is transferred from the incoming solar rays to the holes and electrons in the silicon to overcome the junction barrier voltage and to establish current flow in the external circuit.