

Solar power from satellites

The combination of solar energy collectors in synchronous orbit with receiving stations on Earth, linked by microwave power-transmitting beams, could be economic, safe and environmentally acceptable.

Peter E. Glaser

Various alternative energy sources have been proposed in the last few years, many of them figuring in the pages of *PHYSICS TODAY*. The recognition that no one of these energy sources will, by itself, meet all future power needs, together with the large uncertainties inherent in the achievement of full potential for each of them, has led to what might appear the most daring proposal so far: large-scale solar-energy conversion in space with a satellite solar-power station located in synchronous orbit around Earth—that is, at an altitude of 22 300 miles above the surface.

The satellite power station could use one or more of several methods to convert solar energy to electricity on a nearly continuous schedule. This electricity could be fed to microwave generators incorporated in a transmitting antenna in the satellite, and the antenna would direct a microwave beam to a receiving antenna positioned in a direct line of sight on Earth. There the microwave energy could be reconverted safely and efficiently to electricity and fed into conventional power-transmission networks. With additional satellite systems, power could be delivered to almost anywhere on Earth.

Technical and economic feasibility studies of such systems already indicate that they could provide an economically viable, and environmentally and socially acceptable, option for power generation on a scale substantial enough to meet a significant portion of future world energy demands.

Solar-energy conversion in synchronous orbit has many advantages over ground-level conversion. These include:

▶ A satellite in synchronous orbit is ex-

posed to between four and eleven times the solar energy available in those areas on Earth that receive copious sunshine.

▶ The solar energy in orbit is available nearly continuously—the only “black-out” is at short periods around the equinoxes when the satellite is in shadow for a maximum of 72 minutes each day (near midnight at the receiving antenna site, when power demands are lowest). Averaged over a year, shadowing by the Earth results in only a 1% energy reduction compared with continuous irradiation.

▶ Zero gravity and the absence of wind and rain at the satellite's location would permit the building and use of structures with large area and light weight. The vacuum of space makes unnecessary the evacuated enclosures around microwave generators and other components that are required on Earth.

▶ Because the satellite in synchronous orbit (or, more precisely but less familiarly, “geostationary” orbit) would be stationary with respect to points on Earth, the microwave beam could be directed to receiving antenna sites conveniently close to most major power users—so substantially reducing the length of transmission lines.

▶ The environmental effects of the proposed system are expected to be within acceptable limits. All waste heat associated with solar energy conversion and microwave generation could be rejected to space; no waste products would be generated; the microwave beam densities could be designed to meet international safety standards, and the thermal pollution entailed in the reconversion of microwaves directly to electricity at the receiving antenna would be about one-quarter that of conventional power plants. Furthermore, the receiving antenna would be substantially transparent to

solar radiation and open enough for rain to reach the land below it, thus providing opportunities for multiple land use.

Following the original broad concept of the satellite solar-power station, about eight years ago, detailed feasibility and design studies are currently in progress at NASA, Jet Propulsion Laboratory, Boeing, Econ and Rockwell. The industry team working with Arthur D. Little, Inc had responsibility for different segments of the design: Grumman Aerospace Corp. for structure and transportation; the Raytheon Company for microwave components, and Spectrolab Inc. for solar cells. Details of individual contributions will be found in the acknowledgement note at the end of this article.

Two artist's impressions of the design concept now taking shape at the hands of this team are shown in figure 1 and on the cover of this issue of *PHYSICS TODAY*. The current position is that, while the broad outline of the design is beginning to be defined, many options remain within the major areas. Let us look now at the state of development of the technology within each of these major areas, and the options that have been considered.

Converting solar energy in space

As originally conceived, the satellite solar-power station could use any of several current options for solar-energy conversion¹—thermionic, thermal electric, photovoltaic, and others that may be

The satellite solar power station is shown on the cover of this issue of *PHYSICS TODAY* in a general view and here in close-up in two artist's impressions. Solar radiation, concentrated by reflectors, illuminates lightweight, flexible solar-cell arrays; the electrical output is beamed, as microwave power, from the circular transmitting antenna to a receiving antenna and rectifier combination on Earth. Figure 1

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developed in the future. Photovoltaic energy conversion, however, appeared to be the most useful starting point because of the widespread experience with solar cells in the space program. The current "baseline" design uses this approach. There are other advantages, too, to the selection of photovoltaic conversion: ERDA's National Photovoltaic Program has as its objective the development of low-cost, reliable photovoltaic systems; and the reduced maintenance requirements of the passive photovoltaic process (as compared to active conversion processes) should lead to increased reliability during the desired 30-year operational lifetime of each solar-power station.

The alternative methods include thermal-electric conversion, where focussed solar energy operates a heat engine.² Lightweight solar concentrators could focus solar radiation into a cavity receiver, where the heat could be absorbed by a circulating fluid or a gas (say helium) and transmitted to a heat engine, which would in turn drive an electric generator. For reasonable operating efficiencies the overall system would need radiators to reject waste heat to space.

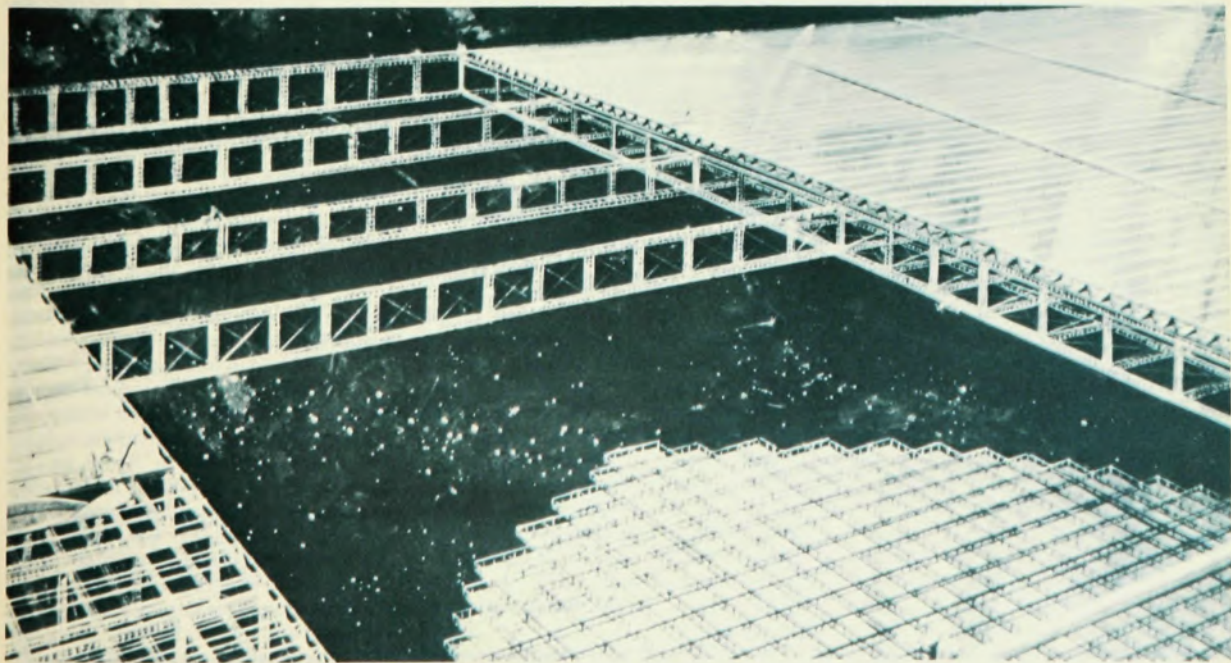
The potential of such a system, particularly one with a Brayton-cycle engine, is sufficient that it is being investigated as an alternative solar-energy converter for the satellite power station.³ The dif-

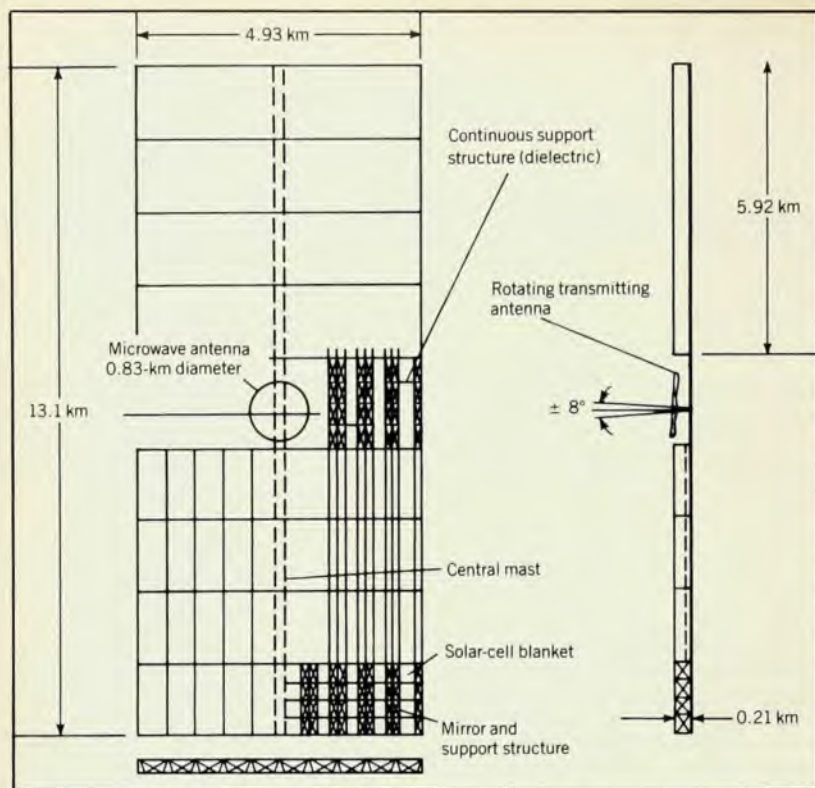
ficulties, however, appear to be formidable, particularly with the need to provide a large waste-heat radiator (about 1 square kilometer in one design) and with the design of the solar concentrators (about 50 square kilometers to drive 48 turbogenerators with an output of 14 000 MW in space).

Transmitting the power to Earth

Power generated within the satellite solar-power station could conceivably be transmitted to Earth, 22 300 miles below, either by a microwave beam or a laser beam, or simply by using mirrors to focus sunlight down to Earth.

Of these options, the microwave





Geometry and dimensions. The two solar collector panels shown here would together produce about 9300 MW (about 5000 MW available power output at the receiving antenna before the power interface). The central mast, 100 meters in diameter, and the stiffened skeletal structure provide rigidity for the flexible solar-cell substrate. The transmitting antenna must rotate once each day (relative to the satellite structure) to remain oriented toward the receiving antenna while the solar-cell array is facing the Sun to within one degree.

Figure 2

method alone uses achievable, demonstrated technology to obtain high efficiency in generation, transmission and rectification. In addition, it promises to satisfy environmental requirements and safety considerations. The mass production of more than one million microwave devices, serving an annual market of half a billion dollars in the US alone, indicates the degree of commercialization of the technology.

Among the optional transmission methods, the laser beam is not acceptable because of the low efficiencies associated with the conversion of electricity into laser power and to eventual reconversion of laser power into electricity, and because of optical limitations. The absorption of laser beams by the atmosphere and by clouds would reduce the overall efficiency even further, to an unacceptable level, and the risks involved to the general public should the beam-direction control system fail are too great. The third option, concentrating sunlight with mirrors placed in synchronous orbit to overcome the diurnal variation of solar energy on Earth, is equally unacceptable—in part because of the large area of mirrors that would be required in orbit for a reasonable concentration factor at a location on Earth, and in part because of the losses from

absorption in clouds. In addition, serious ecological problems might arise from an interference with the diurnal cycle if this scheme were employed.

The current design concept

The design study to be described here represents the present stage of evolution of a series of theoretical, technical and economical studies—which are still in progress. This design⁴ uses silicon solar cells in combination with solar reflectors to convert solar energy into electricity, and it has the potential for large-scale power generation, delivering from 2000 to 15 000 MW to Earth. The lower end of this range represents a satellite power station that could be used to meet incremental capacity demands, and the upper end one that would eventually replace conventional power plants.

Present silicon solar cells are about 200 microns thick and have efficiencies up to 15%. The current design uses silicon cells mounted on rigid substrates with cover glasses bonded to the solar cell for radiation shielding. Flexible substrates with printed circuits to which solar cells can be soldered or welded are being developed for other space applications and may prove superior.

The efficiency of silicon solar cells has

been steadily increasing, due to such techniques as shallow diffusion to increase uv response, non-reflecting solar-cell surfaces, antireflective coatings to improve uv resistance, reduction of current-conductor size to increase the active area, and doping to reduce the degradation of performance induced by energetic solar radiation. The best present-day technology suggests a weight-to-power ratio of about 14 kg/kW, but projections based on improvements expected in the next ten years indicate that 1.4 kg/kW may be achievable. These figures are for designs that incorporate solar concentrators with reflective-film mirrors coated to divert solar radiation onto the cells and filter out undesirable portions of the solar spectrum.

Exposure to the space environment will degrade the silicon solar cells logarithmically, with about 6% of the original efficiency being lost after the first five years. For the thirty-year lifetime of a satellite power station, calculations suggest that one per cent of the cells will be affected by micrometeorite impacts.

The present stage of evolution of satellite solar power station design studies is represented in figure 2. This shows two solar collector panels, each 5.92 km × 4.93 km, together producing a power output of about 9300 MW (resulting in an effective power output at the receiving antenna on Earth of about 5000 MW). Rigidity of this double array is provided by a central mast 100 meters in diameter and a stiffened skeletal structure running through the assembly. Between the two panels is a microwave transmitting antenna; the panels will face the sun continuously while the microwave antenna rotates once each day (with respect to the panels) to face the receiving station. Only the rotating joints necessary for antenna orientation are "active" in what is otherwise a passive satellite.

The entire structure is subject to thermal stresses and distortions induced by thermal gradients during the equinoctial eclipses when the satellite passes through Earth's shadow. The longest eclipse duration is 72 minutes. For such a large structure, oscillations caused by this thermal exposure could be a problem. Fatigue effects might shorten its service life. Structural-design approaches that would minimize the effect have been identified, but more detailed evaluation of the problem is still necessary.

Obviously the satellite must remain fixed in its geostationary orbit at all times, despite the orbital perturbations (some of which are identified in figure 3) that threaten to move it from the desired spot. Ion engines, possibly fueled by argon, will be needed to keep the power station in the appropriate orbit and to maintain orientation of the solar panels towards the sun and the microwave antenna towards the receiving antenna on Earth. The quantity of propellant required for this sta-

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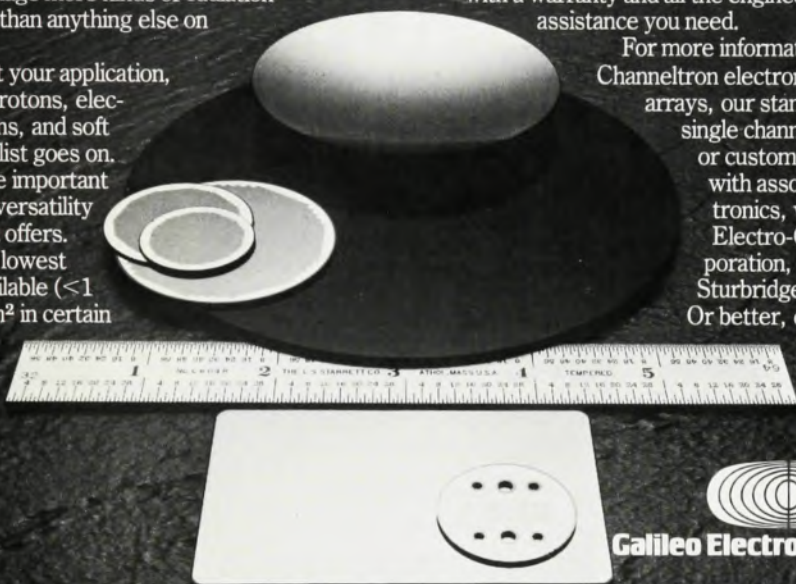
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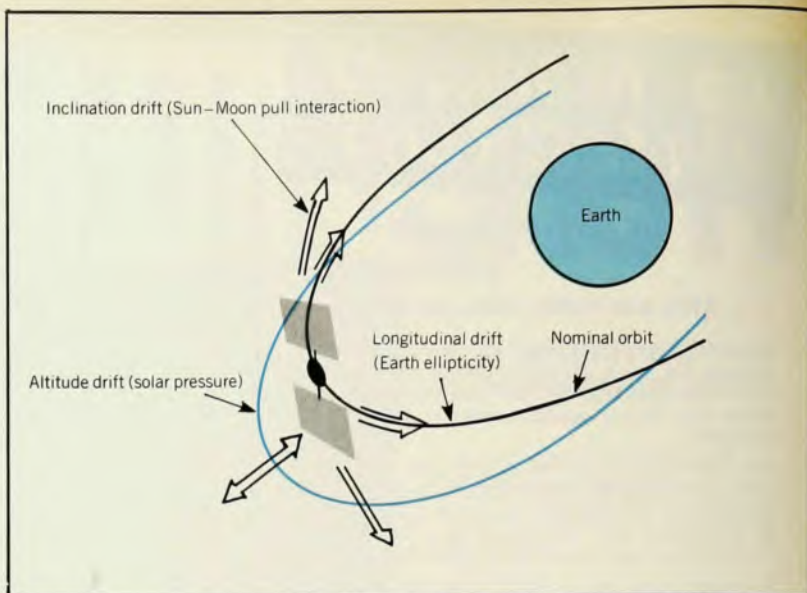
tionkeeping and attitude control is around 50 000 kg per year.

The total mass of such a power station (delivering 5000 MW at the receiving antenna) amounts to 18.2×10^6 kg, not including consumables. Most of this mass, 12.4×10^6 kg, is in the solar arrays with the transmitting antenna adding 5.5×10^6 kg and the remainder being made up by the control system and the rotary joint. The weight/power efficiency ratio of 3.6 kg/kW is remarkably low, compared with that of terrestrial systems, and demonstrates the advantages to be gained by placing the solar energy conversion system in synchronous orbit.

Microwave power transmission

Free-space transmission of power by microwaves is a relatively new technology, but it has advanced rapidly and can already show system efficiencies of 55% including the interconversion between dc power and microwave power at both terminals.⁵ Figure 4 is a block diagram of the system designed for the satellite solar-power station,⁶ with the efficiency goals of each stage.

For converting the dc voltage output from the solar cells to rf power at microwave frequencies either an Amplitron or a klystron may eventually be selected. The Amplitron^{6,7} is a cross-field amplifier with a cold platinum cathode operating by secondary emission to achieve very long life. The Amplitron requires 20kV dc voltage. The weight of the unit can be low enough for this satellite application if special materials are used in its construction—samarium cobalt for the permanent magnet and pyrolitic graphite for the space radiators. The specific weight and cost of the Amplitron are optimum at a frequency in the industrial microwave band 2.40–2.50 GHz and at a power output around 5 kW.



Orbit perturbations. The satellite must remain fixed in its geostationary orbit despite perturbations that threaten to move it from its nominal position. This drawing shows three perturbations: **longitudinal drift** around the synchronous orbit, due to the ellipticity of the Earth's equatorial plane; **altitude drift**, due to solar radiation pressure, which would change the eccentricity of the orbit, and **orbit inclination drift**, caused by the gravitational gradient arising from the pull of the Sun and Moon, which would alter the orbital plane. Stationkeeping and attitude control could be maintained by ion engines, possibly fueled by argon.

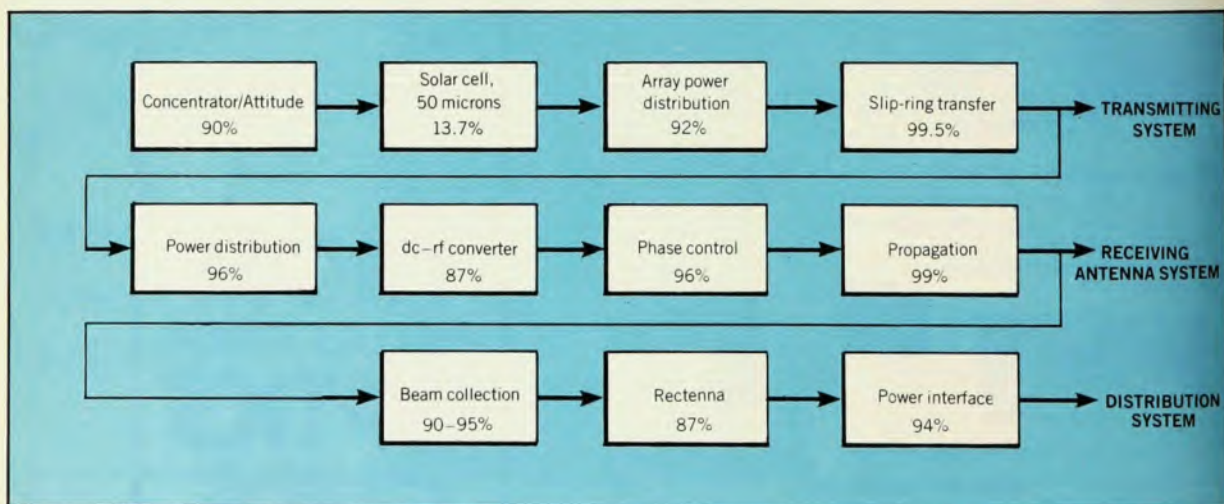
Figure 3

The klystron, a linear beam device, differs from the Amplitron in being a high-gain device with an efficiency only modestly high (70–80%), in contrast to the low-gain Amplitron efficiency of perhaps 90%. Klystrons have low noise properties, whereas the Amplitron's noise behavior is still unknown in this application.

In terms of cost and weight, the klystron is both more expensive and heavier than the Amplitron. But fewer and higher-powered klystrons (such as sole-

noid-focussed units with outputs greater than 50 kW instead of the conventional low-powered, permanent-magnet-focussed klystrons) could simplify the orbital assembly task.

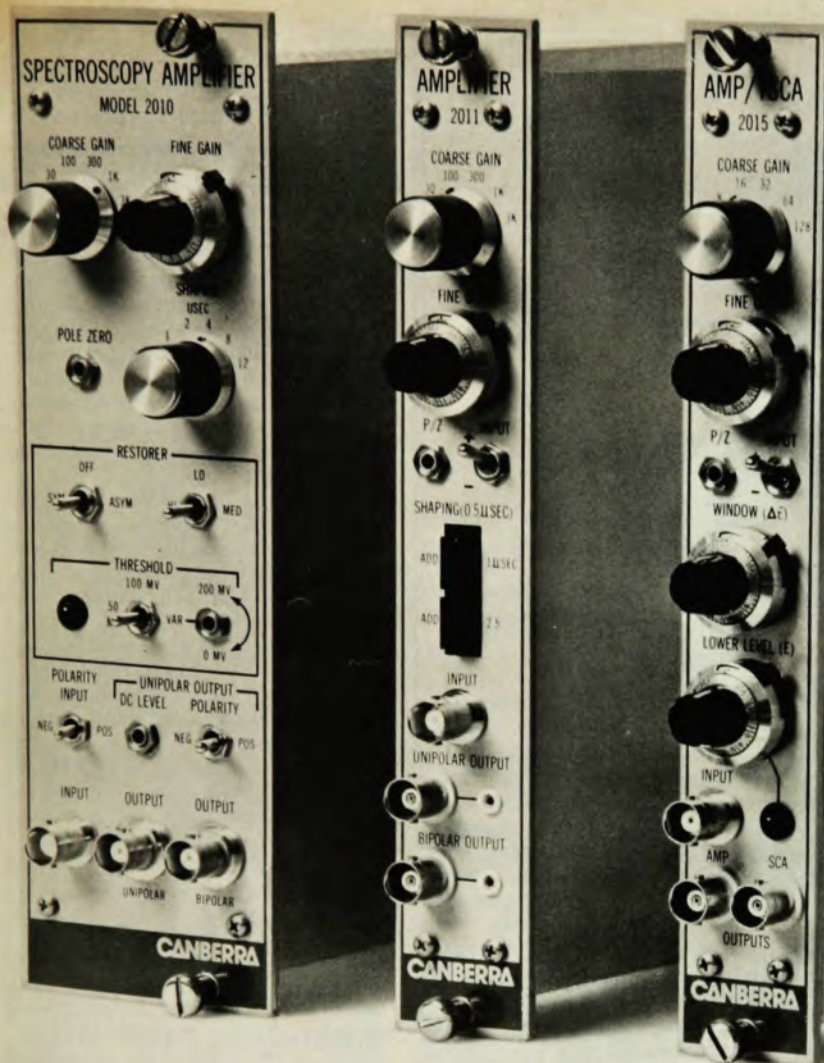
Space is an ideal medium for the transmission of microwaves; an efficiency of 99.6% is thought to be possible for propagation from the point where the beam leaves the transmitting antenna to a point above the upper atmosphere. To ensure high efficiency in transmission for the lowest cost, the geometric relation-



Efficiency chain of the elements that make up the entire system. The figures quoted here are efficiency goals for each stage. For the solar

cells the quoted efficiency, 13.7%, is for a two-panel system, five years into its projected 30-year life span.

Figure 4



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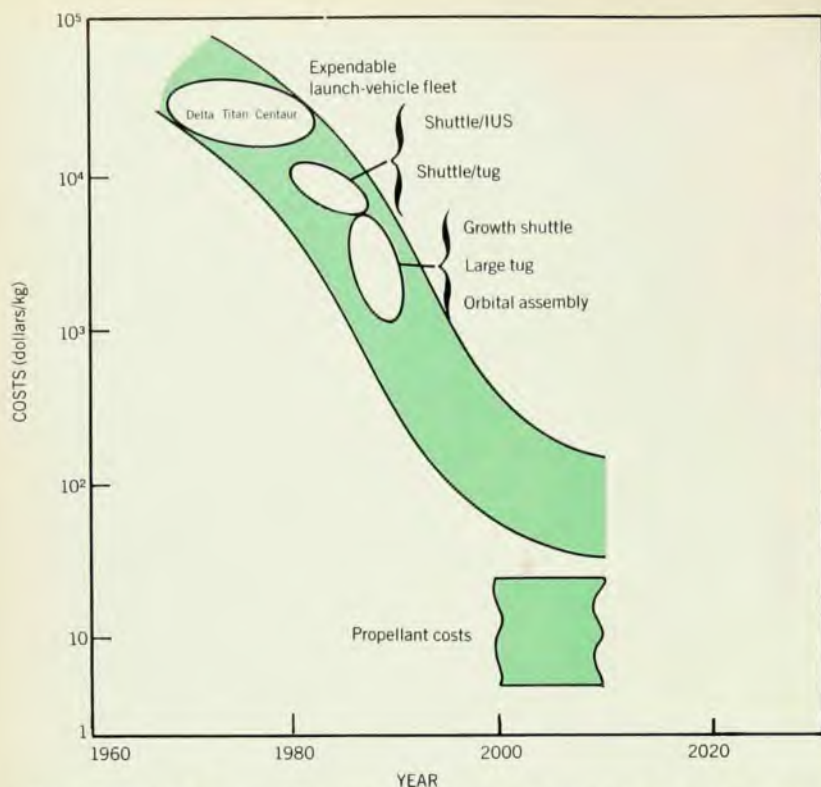
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Payload delivery costs to synchronous orbit in 1975 dollars. The space shuttle is already well along in its development; if this is eventually replaced by a specially designed launch vehicle (perhaps by the year 2000) delivery costs would fall from \$200–400 per kg to \$40–120 per kg. (Source of data: NASA Johnson Space Flight Center, Houston, Texas.) Figure 5

ships between the two antennas^{7,8} indicate that the transmitting antenna should be about 1.0 km diameter and the receiving antenna about 10 km diameter.

The transmitting antenna is designed as a circular, planar active phased array, divided into a large number of subarrays, each approximately 20 meters square. Much emphasis has been placed in the design study^{9,10} on the phasing control system to ensure high efficiency, good pointing accuracy and safe operation of the microwave beam.

Absorption, refraction and scattering effects in the ionosphere are expected to be negligible at the low microwave power densities being considered.

Down on the ground the receiving antenna will be, according to the current design study, an array of elements to absorb and rectify the incident microwave beam; in each element will be a half-wave dipole, an integral low-pass filter, a diode rectifier and a bypass capacitor. The dipoles will be dc-insulated from the ground plane and appear as rf absorbers to the incoming microwaves. The design study shows the dipoles spread about 0.6 wavelength apart, arranged in a triangular lattice about 0.2 wavelength from the ground plane. This distance can be adjusted (within limits) until there is a good match between the specific dc load impedance and the incoming microwave

beam. This match can approach 100%; reflection losses of less than 1% have been achieved experimentally. Tests on the entire "rectenna" element in its current state of development show an efficiency of 90%.

The power density at the receiving point will always be a maximum at the middle of the beam, decreasing with distance from the center. The overall size of the receiving array will be determined by the radius at which the collection and rectification of the power becomes marginally economical. It can be made 80% transparent, so that the land underneath could be put to other uses. Heat generated during the rectification stage (in Schottky barrier diodes made from gallium arsenide material) will amount to less than 15% of the incoming microwave radiation—a source of thermal pollution lower than that of any known thermodynamic conversion process.

The JPL Venus antenna site at Goldstone, California was the location of tests¹⁰ in Summer, 1975 of a 24-square-meter array of microwave rectifier elements constructed according to this design study. The transmitting antenna for these tests, an 86-foot-diameter dish, was about one mile from the receiving array. At a radiated frequency of 2388 MHz, incident peak intensities of up to 170 mW/cm² yielded as much as 30.4 kW of dc

power output from the array. This represents a combined collection and rectification efficiency under these conditions of more than 82%.

Transportation, assembly, maintenance

So far we have discussed efficiency and economics only for a satellite power station fully assembled, in working order and "on station" in its geostationary orbit. But obviously the components have to be transported from Earth to that position, they have to be assembled into the operating array, and the working power station will presumably need maintenance from time to time during its 30-year life. The costs of these operations will clearly have a great impact on the economic feasibility of the project.

As currently foreseen, transportation will be a two-stage process—one stage to low Earth orbit and a second delivering partially assembled components into synchronous orbit.¹¹ The first stage, as presently considered, will utilize either a modification of the space shuttle, which is already well along in its development, or a new heavy-lift launch vehicle. The cost for a modified space shuttle capable of lifting payloads of 80 000 kg to low Earth orbit is projected to be \$200–400 per kilogram; with a specially designed heavy-lift launch vehicle these costs could fall to \$40–120 per kg (figure 5).

Each complete satellite power station will need from 60 to 100 individual flights of heavy-lift launch vehicles. The limits on lifting capability may be set more by the available volume than by the weight-lifting performance of each flight; although some deployment of prefabricated structures (such as the transmitting antenna) at low Earth orbit is desirable, there is a limit to the amount of folding and compressing that can be achieved.

After assembly in low Earth orbit the satellite power station could be lifted to synchronous orbit by ion propulsion. The many challenges inherent in the development of a low-cost, heavy-lift space transportation system for this stage are currently being explored.¹²

To assess maintenance costs before experience is gained with a working satellite power station is obviously difficult, depending as it does on a knowledge of the reliability of the entire system. The costs can be reduced by using a large number of identical components (for example, the solar cells) for redundancy. Also the cost of performing repairs must be compared with the "cost" of delaying repairs and accepting potential loss of revenue. The eventual goal, of course, is the evolution of a completely maintenance-free system.

One option that must be considered under the general heading of "assembly" is that certain components could well be actually manufactured in space.¹³ For example, silicon crystals suitable for solar-cell manufacture could be grown in

the space station from purified silicon produced on Earth, thereby obviating degradation during passage through the Van Allen belt. Fabrication and assembly of structural components could be done in orbit from appropriately prepared flat-rolled stock.¹⁴ These and other similar techniques would ease the transportation problem because the materials would be lifted into orbit in their most compact form, so reducing the number of orbital flights required. NASA's present study¹³ of the role of space stations is the logical first step in the establishment of such space manufacturing activities.

Environmental implications

The benefits of this (or, indeed, any) large-scale power generation system must be weighed against potential dangers to human health, destruction of valued natural resources, and intangible effects that might influence the "quality of life." Failure to take these steps is demonstrated by the difficulties met by such counter-examples as the supersonic transport aircraft, nuclear power, and interstate highways.

The major social costs of environmental impacts of the satellite solar-power stations appear to lie in: resource allocations (land management, energy requirements for both construction and operation, etc.); environmental degradation (waste heat disposal, interactions with the upper atmosphere, environmental modifications, etc.), and public safety (long-term exposure under normal operations, effects on communications, safety under accident or abnormal situations, continuity of power generation and effects of interrupted operations, etc.).

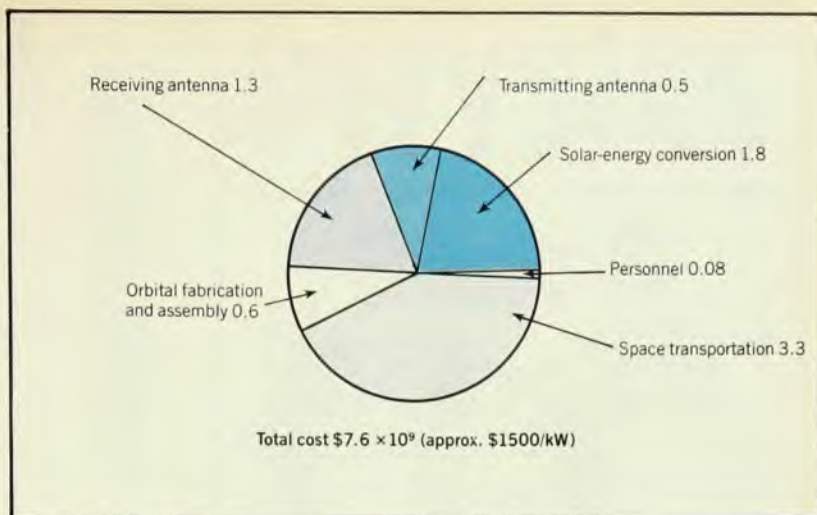
Specific examples of environmental impacts are:

► **Waste heat released** at the receiving antenna site could be limited to 15% of the rectified power, which is, as stated above, much less than from alternative power-generation methods.

► **Land despoilment.** Land use per power station would be about 270 km²; but as stated earlier the receiving antenna would be about 80% transparent to sunlight, impervious to rain, and no barrier to the productive use of the land beneath it. There need be no microwave radiation beneath the antenna, and transportation of supplies to the site (and maintenance operations) would be infrequent compared with conventional power plants. Offshore locations could be considered as antenna sites.

► **Resource consumption.** The materials necessary for construction are largely those in plentiful supply, such as silicon and aluminum. Each satellite power station would need less than 2% of the yearly supply of critical materials, such as platinum, available to the US.

► **Energy consumption.** The energy required to produce the materials for power-station construction and the pro-



Breakdown of unit cost of a 5000-MW satellite solar power station. Costs shown are in units of 4974 dollars $\times 10^9$. This breakdown shows clearly that space transportation is by far the largest cost element, and therefore represents the area where improvements in efficiency and weight reduction would have the most significant effect. Figure 6

pellants to place each satellite into orbit would be regenerated in about three years of operation.

► **Atmospheric pollution.** Space vehicles using liquid-hydrogen and liquid-oxygen propellants are expected to add primarily water vapor to the atmosphere. Heating of the atmosphere would be very small.

► **Ionospheric interactions.** At a microwave power density of 20 mW/cm² or less within the beam no interactions are expected with the ionosphere. Changes in electron density caused by power densities greater than 20 mW/cm² and frequencies higher than 2.45 GHz, however, need to be investigated for possible effects on other users of the ionosphere.

► **Microwave exposure** can be controlled by providing suitable enclosures for the maintenance crew working on the receiving antenna. Beyond 10 km from the beam center the microwave power density would meet the lowest international standards for continued exposure to microwaves. If the microwave-beam pointing system were to fail, the coherence of the beam would be lost, the energy dissipated, and the beam spread out so that the energy density would approximate communication-signal levels on Earth. The effects on birds and on aircraft flying through the beam are projected to be negligible, but they should be experimentally determined.

► **Radiofrequency interference** by the fundamental microwave frequency and its harmonics, turn-on and shut-down sequences, random background energy and other superfluous signals emanating from the microwave-generation devices could be controlled by filters, choice of frequency and narrow-band operation. The effects on radioastronomy, shipborne radar and communication systems will

need to be determined before specific frequency allocations can be made. It appears very possible, for example, that amateur sharing, state-police radar, and high-power defense radar will suffer substantial interference if 3.3 GHz is chosen as the fundamental frequency.

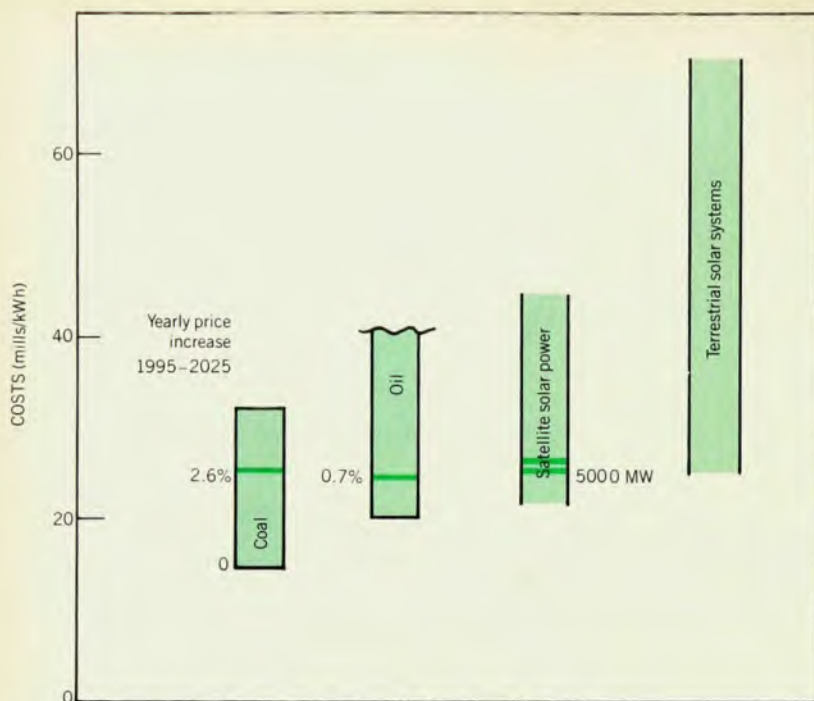
Economic implications

The results of investigations¹⁵ made to compare the economics of the satellite solar-power station with those of the other alternatives show that an operational 5000-MW power station would cost about \$7.6 billion, or about \$1500 per kilowatt. Figure 6 shows the breakdown of this total. Note that the largest cost element is for space transportation, which indicates that improvements in efficiency and in weight reductions would be significant.

For an operational life of about 30 years the cost of power at the bus bar would be 27 mills/kWh. Expected life-cycle revenues will be about \$35 billion for each satellite power station, while operating costs will amount to \$4.2 billion for the same period.

Of course the development program will be expensive—say \$20 billion for the power-station technology and another \$24 billion for the transportation system and related matters—but these costs would be repaid if 60 satellite solar-power stations were operating by the year 2014 (assuming that the cost of generating electricity by alternative means averages 35 mills/kWh). This number of satellite power stations would provide at least 10% of incremental installed generation capacity in the US.

Figure 7 compares the range of projected generation costs for fossil-fueled and terrestrial solar-power systems with



Range of power-generation costs over the period 1995 to 2025 compared for coal, oil and both terrestrial and satellite-based solar power systems. A 5000-MW satellite power station would be competitive with fossil fuels at the projected cost of 27 mills/kWh. Both coal and oil prices are expected to rise in this period. (Costs shown are based on 1974 dollars; source of the data is Econ, Inc., 1975—see reference 15.)

Figure 7

those of the satellite solar-power system. A 5000-MW operational satellite power station will be cost-effective with fossil fuels at the projected bus-bar cost of 27 mills/kWh. Between 1995 and 2025, coal prices are projected to rise by as much as 5% because of increased production costs and the additional cost of pollution-control equipment. The relative price rise of oil is expected to be more pronounced; indeed, it is unlikely to be available at any price after 2000 for large-scale power-generation purposes.

The development program for this project, by any measure a major program ranking with nuclear fission and fusion or satellite telecommunications in scale of effort, will demand careful planning. The best route appears a three-phase program: a first phase of technology verification, largely carried out on Earth, and culminating in an orbiting test facility; a second stage leading to a prototype system (say 200-750 MW), and finally the mass production of full-size units with the goal of at least a hundred 5000-MW stations by 2025.

Since the concept was first proposed in 1968, academic, industrial and government groups in the US and abroad have been assessing the feasibility of the satellite solar-power station. These studies find the concept to be promising, both technically and economically, and environmentally acceptable. They also find that critical developments in technology

needed for the satellite power stations would be useful contributions to other worthwhile developments in space and on Earth—and, conversely, developments already being studied for advanced space-transportation systems, solar energy conversion systems, and other related programs could be of help to satellite power-station technology.

This undertaking, because of its magnitude, worldwide implications on energy availability and potential for the industrial use of space, could benefit many countries. Agreements on such matters as frequency assignments, launch sites and receiving-antenna locations would then become areas of international concern, and decisions would need to be made in the common interest as we look forward to a new era of worldwide energy resource development.

* * *

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