POWER WITHOUT POLLUTION

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Energy is being recognized as the limiting resource in an industrial society. While demands are being made to increase energy production, the potential impact on the environment and the exhaustion of natural resources, associated with present and planned production methods, has caused demands to be made for a reappraisal of these methods. Viewed on the time scale of human history, exhaustion of the world's fossil fuel will be but an ephemeral event lasting a few centuries [1]. This rapid exhaustion of our basic fuel can be readily understood when one considers that the world demand for electrical power is doubling about once every decade, and is expected to continue to do so until living standards throughout the world have been equalized and some form of population control has been achieved.

At the present, all efforts to meet the energy crisis are keyed to a single energy source, nuclear power, and to a single technology, the fast breeder reactor. However, other options need to be explored so that each major potential energy source, fission, fusion, geothermal, tidal, oceanic or solar, can be put into perspective with its more conventional competitors.

The source of energy within the nucleus of an atom is certainly large enough to provide for future large-scale power generation needs, whether it be released by the fission of certain heavy isotopes or by the fusion of the lighter isotopes. Also, this energy source may yet make man independent of other terrestrial energy resources. However, the deleterious effects on the ecology of the earth are now being recognized as possible limitations on this source of energy. In fact, the ecological consequences of the presently known sources of energy represent the most important obstacle to an increase in the generation of power and its associated industrial activities in the future. The ecology of the earth simply may not be capable of sustaining, or even tolerating, the growth of power generating capacity so long as power plants are based on the principles of thermodynamics and have to utilize the surface of the earth or its atmosphere as a heat sink or as a repository of its waste materials. Because of these potential consequences, serious consideration is being given to reducing the rates of industrial growth and thus achieve a period of stability. However, slower industrial growth has in it the inherent danger of cultural regression.

This uninviting prospect is based on the assumption that there is no alternative energy source and that the conversion of an energy source into its most useful form, electricity, is limited in efficiency to that possible through the Carnot cycle. Direct energy conversion, which invokes the principles of quantum mechanics and which relies on the solid-state behavior of materials, opens up new ways to tap the energy source which has sustained life on earth, the sun.

Utilization of the sun's energy is an old dream [2-6]. Solar energy has long invited collection and conversion into other useful forms, such as mechanical and electrical power, but past attempts have not shown enough economic promise to find widespread application. Recent developments in science, particularly in solid-state physics and in applied technology — as exemplified by the complex hardware required for space exploration; by advances in photovoltaic conversion of solar energy; and in the generation, transmission, and conversion of microwaves to generate power — add a new dimension to the concept of pollution-free power from solar energy.

The primary advantage of any large-scale use of solar energy is the inherent absence of virtually all of the undesirable environmental conditions created on earth by traditional means of power generation. Which of the approaches, now being proposed for large-scale conversion of solar energy [7-10], will become the most feasible alternative to present power generation methods, remains to be established. Therefore, efforts to provide details on various methods of converting solar energy to power should be recognized as worthy of increasing attention.

Concept of a Satellite Solar Power Station

One approach is based on the concept of a satellite solar power station. An artist's concept of a system of such satellites placed in synchronous orbit with the earth is shown in Figure 1. Each satellite consists of arrays of solar cells to collect and convert solar energy to electricity, a transmission cable to supply the electricity to microwave generators, and an antenna to beam the microwaves to a receiving station on earth, where they could be converted to electricity (Fig. 2).

A synchronous satellite in an equatorial orbit will remain stationary over a point on the earth's surface. It would be exposed continuously to the sun, except near the spring or fall equinoxes, when it would be eclipsed by the earth for a maximum of 1 hour 8 min. These short periods of nonexposure can be overcome by using at least two satellite solar power stations, each displaced in an orbit from the other. Another solution would be to place the space power station in a nonequatorial orbit with a seasonal rhythm pattern. The satellite power station would no longer remain stationary with respect to the earth's surface but would appear to move up and down the southern horizon with a 24-hour period, the swing being the greatest during the equinox period.

The electrical and physical size of a typical system are illustrated in Figure 3. The system is scaled to deliver 10 000 MW of electrical power to the earth, enough to supply New York City and its surrounding area. Based on a solar array efficiency of 10 percent, the solar collector would cover 25 square miles. The microwave power transmission system would be designed to operate at a wavelength between 10 and 20 cm so the beam of energy would penetrate the earth's atmosphere with a very low loss, even under adverse weather conditions. A transmitting antenna, 1 square mile in area, designed for operation at a wavelength of 10 cm, and located in synchronous orbit 22 300 miles from the earth, can be designed to focus 99.9 percent of the generated microwave energy into a 25-square mile area on the earth's surface [11]. Outside of that receiving area, the density of the incident microwave energy will be negligible. Even within the area, the collection of the microwave energy will be so efficient that with the possible exception of the immediate center of the area, grazing animals, for example, would be unaffected by the microwaves.

The microwave power transmission system consists of three major parts:

1. Microwave generation, the conversion of the dc power output from the solar cells into microwave power

2. Beam forming, focusing the microwave energy into a sharp beam by means of the transmitting antenna

3. Microwave collection and reconversion to electrical energy.

High efficiencies have already been demonstrated in all three segments of the system [12]. Additional development effort promises to raise the conversion efficiencies at both the transmitting and receiving end to 90 percent. While the efficiency of microwave beam transmission can be raised to virtually 100 percent, cost considerations would probably indicate some lower efficiency. Nevertheless, the transmission efficiency would still be far in excess of any comparable conventional earthbound power transmission system.

The power-handling capacity of a transmission link in free space is virtually unlimited. Furthermore, it can be upgraded by adding additional elements to the solar cell array, additional or higher-powered conversion elements at the transmitting end, and higher-powered elements at the receiving end. Neither the area of the transmitting antenna nor that of the receiving device on the ground needs to be increased. Thus, a system, once installed, has ample opportunity for power growth without the need for additional real estate on the earth.

At first glance, the very high power levels associated with the system do not seem to be consistent with a microwave technology, usually identified with the lower power levels common in the communication industry. However, high-power tubes with high efficiencies have been developed and await applications [13]. To be sure, no single tube now available can supply 10 000 MW of microwave power, but even if one were available, it would not be used. Transmitting antenna construction and service reliability are more likely to favor the use of several thousand transmitting tubes on a one-phase array. Such an array would reduce the rating of the individual tubes to the point where their design would be consistent with a modest extension of existing tube technology.

What if we should need transmitting tubes with individual ratings of a magnitude two or three orders greater than those in existence? Very likely, they could be designed by taking advantage of one or more recent developments. The availability of samarium cobalt as a permanent magnet material, for example, permits an order-of-magnitude decrease in magnet weight for microwave power generators.

The power-handling capability at the receiving end is based on a device called the rectenna [14]. This device is nondirective and can be made in the form of a lightweight web supported on posts. It uses highly efficient Schottky barrier diodes, whose efficiency and power-handling capability are being improved continuously.

The satellite solar power station and the microwave power transmission system would use considerably less copper than would a traditional power generation facility of an equal power rating. Hence, the solar space power station would help conserve this and, perhaps, other critical materials.

A system of space power satellites could provide a nearly inexhaustible source of electric power. A belt of solar cells 3 mi wide in a synchronous orbit around the earth would intercept 1.68×10^{15} W of solar energy. Even if there were no improvements in solar cell efficiency, 8 percent of this power, or a total of 1.34×10^{15} W, could be made available in the form of dc power to widely distributed locations on the earth. Such a power level would provide 1.17×10^{15} kW-hour of electrical energy per year, or more than 200 times the projected world electrical energy requirements for the year, 1980. As conversion efficiencies of solar cells and of other system components were increased, satellite solar power stations would be able to keep up with increasing world energy demands.

Such a huge potential for electrical power generation might well provide the necessary leverage to conserve our fossil-fuel sources of energy, now used, not only for electrical power generation, but also for many other energy requirements.

Systems Considerations

System engineering and management techniques, developed to direct and control massive engineering undertakings, have contributed heavily to the success of the space program. The development of a satellite solar power station would have to call on these techniques to determine the size and capacity of each component of the system, to predict the performance of the assembled components for the various system configurations, to estimate the dependency of the performance of the component charac-

The major components of the system (Fig. 3) will have to be well defined, the components identified as to function and type, the sequence in which they are connected established, their functions analyzed, and the differences among various approaches reconciled. Although candidates for most of the components now exist, at least in the form of laboratory models, new and quite different components can be expected to be developed. How each will perform if fully developed is uncertain, but systems engineering techniques can be used to approximate and compare the performance and costs of the various system configurations, to estimate the dependency of the performance of the component characteristics, and to set quantitative targets for component developments based on forecasts of component technology and performance.

A reusable space shuttle is expected to result in significantly lower costs for orbiting payloads in the 1975-1985 period. As envisioned, the Space Shuttle will be capable of carrying payloads of 50 000 lb. Succeeding generations of space transportation systems would be expected to have substantially greater payload-carrying capacities. Over a period of several months, a Space Tug, powered by ion engines, could transport to synchronous orbit modules of a satellite station that had been assembled in a train in a low earth orbit. Alternatively, a reusable nuclear stage could be used to transport the modules between low earth orbit and synchronous orbit.

The concept of a satellite solar power station rests on the availability of an efficient and economical space transportation system. Its successful development over the next decade will depend on solving many technical problems that are being addressed in our efforts to place large manned space stations in orbit. Thus, the capability to produce large structures in space, which will be essential to assembling the modular space stations envisioned for future missions, should be available during the next decade [15]. The experience gained in the assembly of such large structures by human operators, subsequently, with the help of automated teleoperators, will be a step toward a satellite solar power station.

Technology Status

Solar Energy Conversion. Silicon solar cells have been the primary source of electric power for almost all unmanned spacecraft, both for space exploration programs and for the application of space technology to communications, navigation, and meteorology. Improvement of the technology of silicon solar cells has been accelerated by the increasing requirements of large spacecraft for missions in earth orbit and for exploration of the planets. Solar cell arrays have grown from a few square feet, to the lightweight deployable solar cell arrays of several thousand square feet, and power levels of tens of kilowatts now being applied in the Skylab spacecraft.

The N/P silicon solar cells, with their superior radiation resistance and good control over mechanical and electrical tolerances, have been the mainstay for space missions. New processes, such as the manufacture of solar cells from webbed dendrite silicon or from extrusion of a ribbon of silicon single crystals, are expected to increase the cell size, and thus, reduce cost, especially for the large solar cell arrays. Lithium-doped silicon solar cells have the potential of providing a fiftyfold improvement in radiation resistance over the conventional N/P silicon cell [16]. Rollout solar cell arrays with a specific power of 30 W per pound, within the state of the art and further improvements can be anticipated [17].

The most significant long-term opportunity is for a major advance in photovoltaic efficiency. While the single-transition silicon solar cell is theoretically limited to efficiencies of 25 percent, with about 10 percent attained in practice, solar cells with higher efficiencies are possible. A multicellular device, for example, consisting of two or more photovoltaic layers in a sandwich configuration, could use wavelength bands where the materials have high quantum efficiencies and thereby increase overall efficiency considerably. Attained efficiencies of 20 percent are considered feasible in the near future [18].

Organic compounds which slow characteristic semiconductor properties, including the photovoltaic effect [19], have only recently been considered as possible energy conversion devices. At present, their efficiencies are only a fraction of a percent, but efforts are underway to synthesize polymers with good photovoltaic characteristics and to study the behavior of other organic compounds [20].

Transmission of Electrical Power. Electric power produced through photovoltaic conversion will have to be gathered at the solar collector and transmitted to the microwave generators. The high power levels may require that the transmission line be superconducting to reduce weight and power losses. To transmit 10^7 kW (20 kV at 5×10^5 A), for example, would require two conductors of a 2-in. diam cooled to about 15° K, and each suitably insulated. The state of the art of thermal insulations for this purpose is well advanced, and proper design would reduce heat losses to a minimum [21]. Multiple-staged refrigerators would provide the desired temperatures over the length of the transmission line. At the superconducting temperature, 1000 W of refrigeration capacity would be sufficient to cool the line and to absorb heat leaks at the cable ends. Such refrigerators have already entered an advanced development stage and would be adaptable for this purpose.

The transmission line, itself, would have to be articulated to provide relative movement between the solar collector and the antenna. The solar collector will have to be approximately pointed at the sun, while the microwave radiating antenna will have to be accurately beamed to a receiving antenna on earth, thus relative motion between the solar collector and the antenna will have to be provided. Rotary joints at the warm end of the transmission line with low friction and capability to carry the power would have to be developed. Experience with movable joints, their lubrication requirements, and the influence of the space environment on frictional characteristics would provide bench marks for this development [22].

Guidance and Control. The large structures which will have to be guided and controlled, particularly the antenna required to beam the microwaves to earth, will require that the state of the art of guidance and control systems be extended to achieve desired position control. The pointing requirements for the solar collector which will have to face the sun are less stringent. Combinations of sun sensors, or star trackers could provide the desired pointing accuracy of about 1 deg. Except for the size of the structure which has to be controlled, the types of devices required are within the state of the art.

The microwave beam will have to lock onto the earth-based receiving antenna and to stray less than 500 ft in any direction. A perimeter of land 1 or 2 mi wide surrounding the antenna may be necessary to assure that the microwave power density not absorbed by the antenna will be below stated limits outside this area. This is desirable, not only to maintain a high efficiency for transferring microwave power, but also to assure environmental safety during operation. To achieve this accuracy would require pointing the microwave radiating antenna to about 0.5 sec of arc. Although this requirement stretches the present limits of attitude control techniques and pointing accuracies, the significant advances in guidance and control over the last decade indicate that this technology could be extended to meet the requirements of a satellite solar power station.

A guidance and control system will have to deal with the forces acting on the satellite to maintain a circular orbit. Among these is the radiation pressure acting on the solar collector and, to a lesser extent, on the antenna. The force, in a direction opposite to the sun, on the solar collector, will be about 300 N; this force will be partially averaged out during an orbit. The force in a radial direction away from the earth, on the antenna, will be about 200 N; this force would have to be counteracted with thrusters. Gravity gradients will introduce a torque about an axis perpendicular to the equatorial plane, as long as a circular equatorial orbit is maintained. Counteracting continuous angular displacement will require thrusters. High specific impulse could be achieved using ion engines, which would be an outgrowth of present technology [23].

Cooling Equipment. The microwave generators will have to be cooled, because heat is generated at the cathode and the anode of each generator. The amount of heat is a direct function of the efficiency of the generator system. If a multiplicity of small microwave generators is used, the generated heat could be removed by means of heat pipes or space radiators distributed over the structure of the microwave radiating antenna. The efficiency of the heat pipes and space radiators would affect the overall weight of the satellite structure significantly. The technology of heat pipes, for instance, has been advancing rapidly and projected weights of 0.1 lb/kW appear to be feasible [24]. The state of the art of coatings and thermal insulations to attenuate and control the flow of heat has advanced to the stage where it can be thermally controlled.

Detailed designs and concepts for a satellite solar power station have not yet evolved to the point that firm cost estimates can be made. However, the first step toward this goal can be taken by projecting from the present state of the art in the direction that future developments may have to take. The assumption can be made that a system of satellite solar power stations should be capable of providing a significant portion of U.S., and eventually world, energy needs. Thus, the design and development of components will require that they be mass produced on a very substantial scale. This is in sharp contrast to present techniques and the resulting costs associated with the production of space flight hardware.

Should the option for energy production based on satellite solar power stations be found to be desirable, the establishment of an industrial base, not unlike that existing in the consumer electronics and the automobile industry, would be a result. The satellites lend themselves to mass production because there are only a few different types of components. Production will involve the replication and assembly of large numbers of components, such as solar cells, microwave generators and microwave rectifiers. In an optimum design, the structure of the satellite will largely be formed by the components and the required electrical interconnectors.

Major components may be assembled in synchronous orbit with assembly techniques, perhaps, based on the use of automated teleoperators. Certain of the components could be formed in an orbital assembly facility to utilize the low-gravity conditions to fullest advantage. Similarly, once in orbit, materials and components could be refurbished; e.g., annealing of solar cells, to extend their operating life. The development of radiation resistant materials, such as solar cells, indicates that the space environment will be more benign than the terrestrial environment, with its continued physical and chemical eroding processes acting on solar energy conversion devices, and 30-year lifetimes for solar cells can be projected in space.

The twin goals of design for mass production and extended operating life are a strong indication of the potential for substantial innovation, as work on a satellite solar power station progresses. A number of analogous advances in technology have taken place as the need for innovation in certain areas was recognized. Examples are the 10 percent efficient solar cells, developed in 1953; the first payload orbited, in 1957; and the first transmission of microwave power, in 1963. Should technical, economic, and social feasibility studies indicate that satellite solar power stations deserve a major effort, the development time of about 20 years would not be unlike that required for nuclear power development.

Cost projections, based on an extension of presently known technology, indicate that a satellite solar power station would generate power at two to five times the cost of competing power generating plants. Additional developments may reduce the presently projected cost differential. However, before meaningful cost comparisons can be made, it will be necessary to arrive at a method of cost accounting, which establishes true environmental and social costs chargeable to each energy production system, rather than comparing systems only on the basis of capital costs and interest.

Conclusion

The large-scale use of solar energy to generate power without pollution could sustain a highly energy-dependent world culture for much longer than the few centuries associated with fossil fuels or, perhaps, even nuclear power. The potential for making this option available to meet future energy demands will be influenced by continuing efforts to advance space technology. There is a risk that exclusive concern with contemporary problems and short-term solutions, without regard to the future, could lead to a deemphasis of space technology and foreclose the large-scale use of solar energy by satellites.

As yet, it is too early to state what bets should be placed on this option to produce power without pollution. What is required, therefore, is a program of research and development to resolve outstanding technical, economic, and social issues, and to place this concept for using solar energy into perspective with respect to both conventional sources of energy and its more exotic competitors. Only with this information in hand can actions be initiated to develop energy sources consistent with a coherent national policy designed to meet future energy demands [25].

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Figure 1. Artist rendering of satellite solar power station.

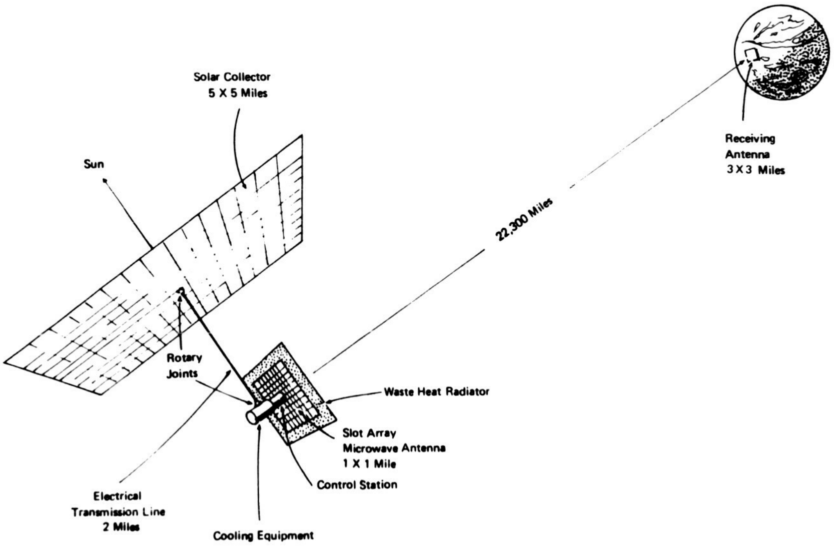
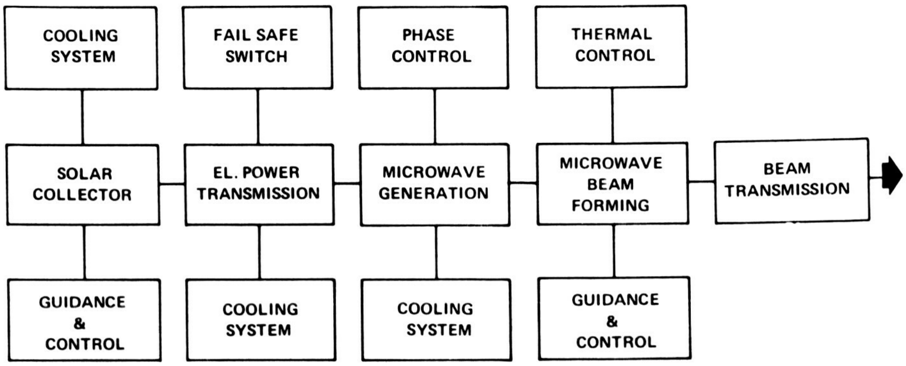
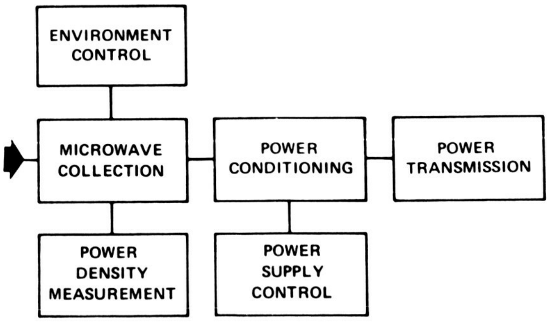


Figure 2. Diagram of satellite solar power station to produce 10 000 MW.

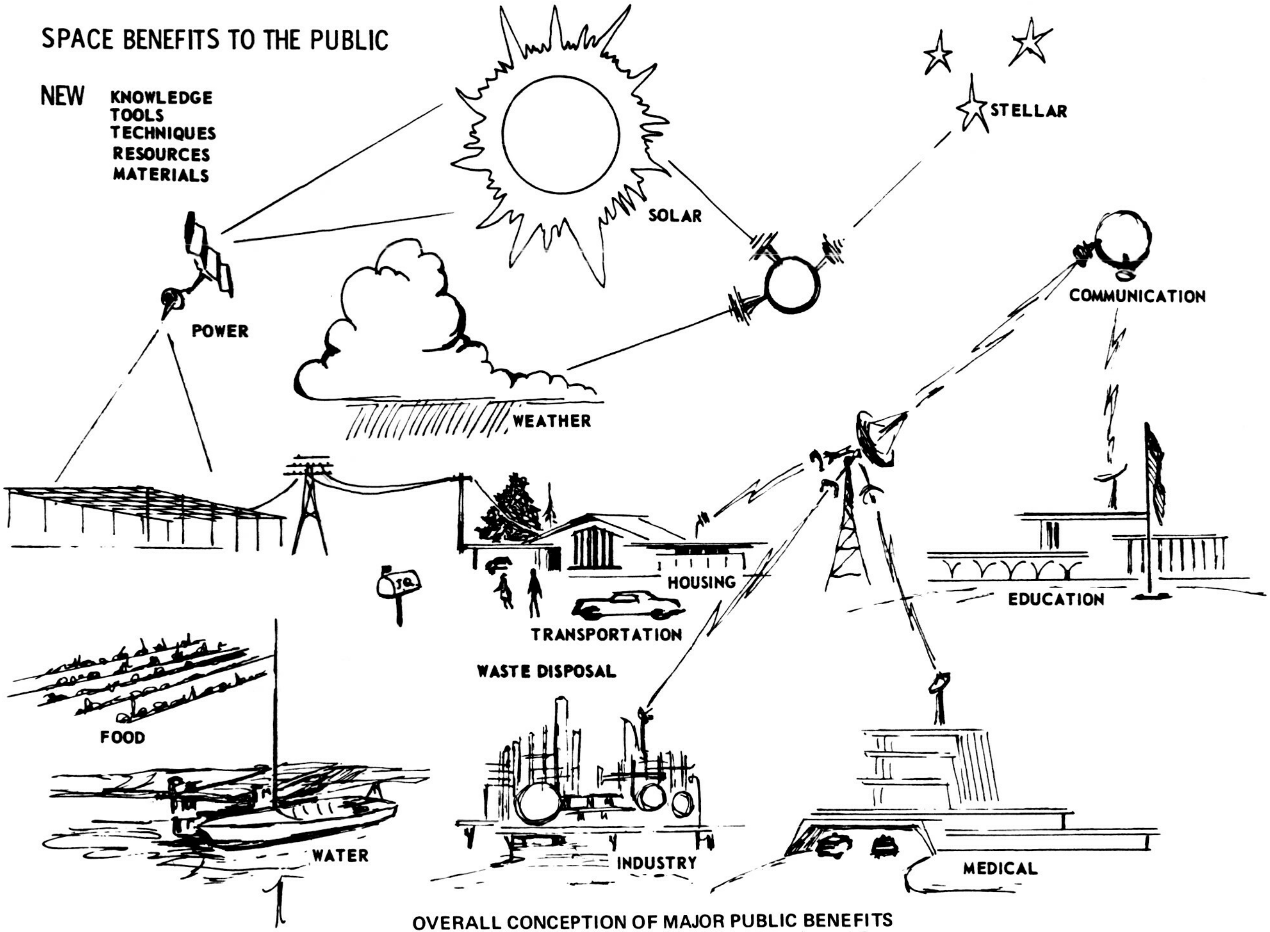


A.
SATELLITE
STATION



B.
GROUND
STATION

Figure 3. Major components of a satellite solar power station.



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