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Power from the Sun: Its Future

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There are three major energy sources available to us today: fossil fuels, nuclear energy, and solar energy. Among these, solar energy is basic to man's continued survival on earth. Although all life would cease should there be a decline in the radiation the earth receives from the sun, solar energy as a significant source of power has not been utilized.

We have been fortunate in that our reserves of fossil fuels have been sufficient to power the machines essential to start modern man on the upward spiral of technological progress. Because we have coal, oil, and natural gas, the tremendous potential of solar energy has not yet been harnessed.

Whether or not the human species will continue to expand could depend on our ability to develop alternative energy sources. Figure 1 shows the transitory nature of the energy which we will be able to derive from fossil fuels (*1*). We can gain a better perspective by considering the annual consumption of energy from fossil fuels in recent history. Fossil fuels represent a finite reserve; the estimated width of the "fossil-fuel impulse function" is only a few hundred years. The decline in the usefulness of fossil fuels will occur when their availability has dropped to around 10 percent of the peak value. The precise location of this point is unimportant; what is important is recognition that the pulse width is a few hundred years, not thousands of years (*2*).

Energy Resources

In Fig. 2 the estimated energy consumption for the United States is projected to the year 2200. By that date, the projection indicates, approximately 30 percent of the total power requirements will have to be met by energy sources other than those available today (*3*). This requirement for new sources represents a definite energy deficiency, which within that time span may well become worldwide. Evolutionary pressures and technological progress will tend to hasten the use of nuclear power, and this will reduce our dependence on fossil-fuel reserves for a time. Should present obstacles in the development of fusion-generated power be removed, our energy requirements may, it appears, be met. However, the control of fusion is still the physicist's dream. It is expected that new physical principles will have to be discovered and huge plants built before useful power from this source can become available to us. To meet the projected power demands, several major obstacles will have to be overcome, and the disadvantages of power-generating processes we are now considering will have to be reduced or offset.

Control of the environmental deterioration that results from our efforts to meet the increasing demands for power from available energy sources will be increasingly more difficult and more costly. Air pollution and water pollution already plague us; in addition, thermal pollution from nuclear power plants could threaten rivers and lakes in heavily populated areas. The need to control this source of pollution has been recognized, and the use of cooling towers may partially solve this problem. But substantial costs would be involved; utility companies may have to spend \$2 billion for cooling towers and related equipment in the next 13 years, in addition to the basic \$19-billion investment they expect to make in nuclear power plants (*4*). (Estimates for U.S. investment in electric-power-generating plants of all types over the next 20 years range up to \$100 billion. (When the investments for environmental control are extrapolated over 30 to 50 years, we can see that our major concern will be alternative approaches, to reduce the cost of controlling undesirable effects on our environment.

One other factor that emerges in a consideration of the increasing per capita consumption of energy is the shift in the kind of fuel consumed. Wood fuel was the dominant source of energy up to 1850; by 1910, coal accounted for 75 percent of the total energy consumption, and by 1960 natural gas and oil represented about 65 percent of the total. It is likely that the expected increase in the number of nuclear generating plants may lead to a switch away from fossil fuels soon after the turn of the century. In the recent past, a significant shift in fuel-consumption patterns required about 50 years. This requirement was the result of factors such as the availability of certain fuels, the economics of the exploitation of resources, and the availability of energy-conversion machinery during the period when the technology was maturing, before new scientific discoveries and innovations found their way into the mainstream of the economy (*2*).

For any technological advance, the interval from conception to widespread

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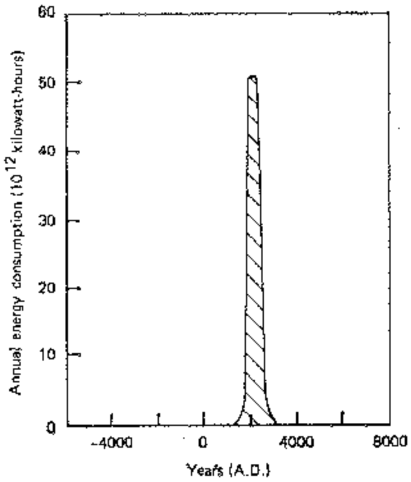

Fig. 1. World consumption of fossil fuel—past, present, and projected [From Hubbert (*1*)]

use has been steadily decreasing; this is true in the field of power generation, and the trends can be projected over the next decades. The increasing demands for power will require the construction of new power stations at a rate which will force the power-generating industry to invest in plants using currently proven processes which in one or two decades may be outmoded. Therefore, nuclear power plants being built today will still be providing power by the year 2000, even though better power-generating plants will have been designed.

When we recognize that there is a significant time lag between the conception and the operation of new power plants, and that there are, moreover, economic pressures for operating such plants, once they are built, for at least 30 years, it can be seen that new energy sources will not be providing power in significant quantities within the next half century. However, the search for alternative energy sources must proceed, so that these will be available when the worldwide demand for energy reaches a point where the adverse effects on the human environment of present energy sources become intolerable. With this longer-range view in mind, we should consider solar energy as our major future resource and should evaluate various means for harnessing it to produce power on earth.

The conversion of solar energy to usable power is the only alternative to nuclear power for the distant future. Prior to the space program, only direct solar-energy conversion had been demonstrated to be feasible. The major successes of the Ranger, Mariner, and Surveyor spacecraft and of orbiting satellites were achieved on power derived from solar cells. At present, the economic desirability of generating power from solar energy on earth is questionable, because of the attenuation of solar energy by the atmosphere, obscuration by clouds, the deposition of dust, the effects of wind on the structures of the generating plants, and the fact that utilization is partial when the sun is near the horizon. However, this need not be the case for the entire time span we are considering here. In future years solar energy will become increasingly essential for the continued evolution of power-generating plants.

Power from the sun is not a new concept. In Pasadena, California, in 1901, a solar steam engine developed 4½ horsepower. In 1902 and 1908, solar engines were built in St. Louis and in Needles, California, which provided up to 20 horsepower. In 1913, a large solar engine was built near Cairo, Egypt, which generated 50 horsepower. The potential benefits, operating requirements, and economics of solar-powered devices have been examined in recent symposia (*5*). In this country solar power was given a tremendous impetus by the requirements of the space program. The literature on solar-energy-conversion devices and associated equipment, as attested by the Intersociety Energy Conversion Engineering Conferences, indicates that we are forming a base on which major advances can be built.

We can distinguish between three major categories of possible uses of solar energy: (i) research uses not necessarily directed toward the production of power; (ii) applications for a wide variety of purposes, including power generation, primarily for developing countries; and (iii) use for power generation in technologically advanced countries. An example of the first category is a solar furnace constructed in France to produce 1000 kilowatts concentrated over a small focal zone, for purposes of high-temperature research (*6*). The second category is the one where most work has been carried out (*7*); examples include solar water heaters, solar distillation plants, and power-generating devices such as solar ponds and solar-powered engines. In the third category, two primary concepts for generating power that are significant in terms of our country's requirements have been advanced. One of these envisions the generation of electric power from the sea by means of a 100-megawatt floating power plant; the warm surface waters of the ocean in areas such as the Caribbean or the Gulf Stream would serve as a heat source, and the cold lower layers, as a heat sink (*8*). The other concept is based on the technological advances resulting from the space program.

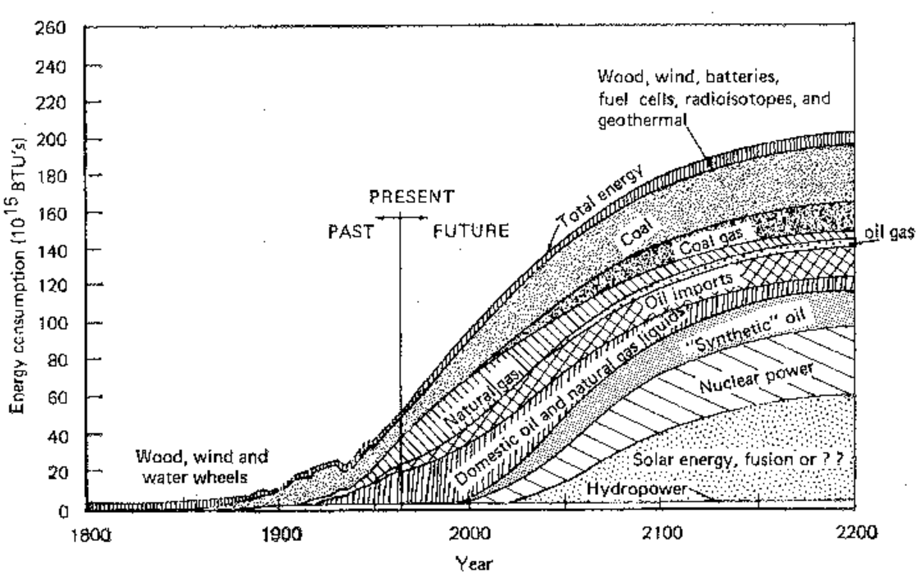

Fig. 2. Energy consumption in the United States—past, present, and projected. [From Gaucher (*3*)]

A Satellite Conversion System

Table 1 shows the annual electrical energy consumption for the United States projected to the year 2000; Table 2 shows the solar-collector surface area required to meet this demand for electrical energy, on the assumption of 100-percent conversion efficiency.

Table 3 shows the estimated surface area and estimated weight of satellite solar collectors for different photovoltaic energy-conversion devices of different efficiencies, exclusive of the weight of structural components. Although the use of satellites for conversion of solar energy may be several decades away, it is possible to explore several aspects of the required technology as a guide to future developments. The following will have to be considered before the feasibility of specific design concepts can be determined.

1) Orbit characteristics such that the satellite solar-energy-receiving area is exposed to the sun and the radiating area can beam energy to any desired point.

2) Solar-energy-conversion devices with efficiencies approaching the theoretical maximum.

3) Transmitters capable of beaming the converted energy to an earth receiving station in a spectral region where minimum atmospheric absorption and scattering are likely to be encountered.

4) Earth receiving stations capable of accepting the required power density and transmitting the energy to power-distribution networks.

Orbit location. One possible system would consist of two geostationary satellites positioned so that at least one would be illuminated by the sun at all times. At an altitude of 22,300 miles (35,700 kilometers) in an orbit parallel to the earth's equatorial plane, a satellite moving from east to west would be stationary with respect to any point on earth. However, the satellite would pass through the earth's shadow once a day; thus two satellites in the same orbit but out of phase would be required, so that one would be illuminated during the time the other was in the shadow (see Fig. 3). To achieve this condition at an altitude of 22,300 miles, the two satellites would have to be about 21 degrees out of phase and about 7900 miles apart. This phase difference would keep the satellites above the horizon, and both satellites would have a direct line of sight to the same point on the earth.

Conversion devices. In view of the present stage of development of solar photovoltaic conversion devices, there is little likelihood that the efficiency and cost per unit weight and per unit collector will be attractive enough to warrant use of such devices for converting significant amounts of energy with a satellite system in the near future. Efficiencies must be higher and weight and cost lower before this can be contemplated.

Current theoretical analyses predict the limit of the efficiency with which a *p-n* junction in a single crystal may convert solar energy into electricity (*9*). The efficiency of conversion of solar radiation to electrical energy is an optimum value which is a "trade-off" between the need for a low-energy band gap for maximum use of all photons emitted by the sun and a high-energy band gap for reducing the effect of thermal diffusion of charge. Even microcrystalline cells based on single-crystal solar-cell principles, which are expected to be developed in the future, will have a maximum theoretical efficiency limit of about 24 percent, which places a definite upper bound on the usefulness of this type of device.

The data of Table 3 indicate that by 1980 a region such as the northeastern United States would require 105 square miles (270 square kilometers) of solar-conversion area (that is, a satellite 11.5 miles in diameter) to meet the projected electrical power demands if presently available silicon photo cells are used for the direct conversion of solar energy. The estimated

Table 1. Annual consumption of electrical energy (in units of 10^{12} kilowatt-hours) for 1966 and (projected) for 1980 and 2000, based on data from *Statistical Abstract of the United Nations*, the U.S. Department of Commerce, and the United Nations *Statistical Yearbook*. (T) Total; (F) fossil fuels; (N) nuclear power; (H) hydroelectric power. [From Starr and Smith (*2*)]

Region	1966				1980				2000
	T	F	N	H	T	F	N	H	T
World	3.34*				6.5				20–30
United States	1.06	0.95	0.05	0.2	2.74	1.80	0.6	0.3	9.0
Northeastern U.S.	0.22				0.50				1.20
South Atlantic U.S.	.20				.45				1.08
New York City	.04				.08				0.19

* 1965.

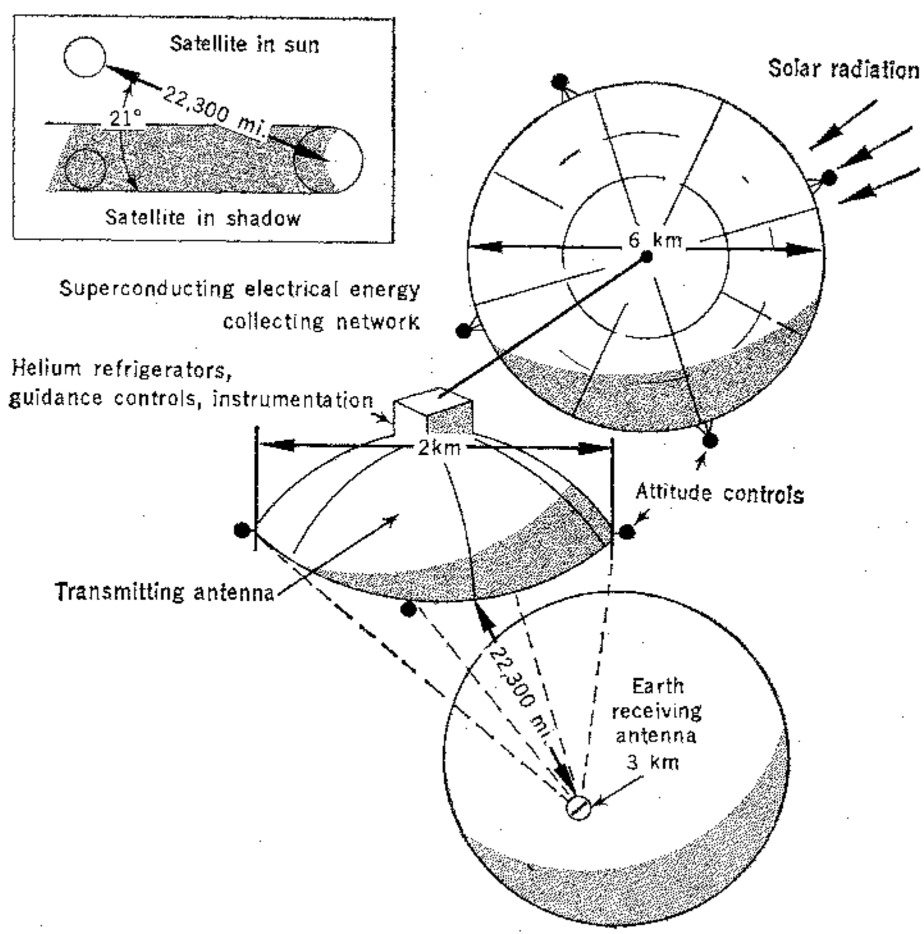

Fig. 3. Concept for a satellite system for the generation of solar power.

Table 2. Solar-collector surface area (in square miles) needed to supply the demand for electrical energy shown in Table 1, on the assumption of 100-percent conversion efficiency. Solar energy available in orbit is taken to be 0.14 watt per square centimeter. [Estimates by Arthur D. Little, Inc.]

Region	1966	1980	2000
World	105	204	630–946
United States	33	86	284
Northeastern U.S.	6	16	38
South Atlantic U.S.	6	14	34
New York City	1	2	6

weight of 1.8×10^8 pounds (81.5×10^6 kilograms) makes this approach unattractive.

An alternative approach is the search for an entirely different type of material for solar-energy conversion. Organic compounds have been found that show characteristic semiconductor properties, including the photovoltaic effect (*10*). Development of organic semiconductors is still in an early stage. However, both theoretical and experimental results suggest that organic systems could provide the efficiency, weight, and cost reductions needed if these large solar collectors are to become a reality.

The future development of photoconductive organic materials which exhibit photovoltaic effects could provide thin-film solar cells each of which would consist of (i) a transmitting conductive upper coat, (ii) a conductive ultraviolet-absorbing coating to protect the photoconductive polymer and to convert the ultraviolet radiation to usable near-ultraviolet or visible light, (iii) a polymer film exhibiting a high photovoltaic effect (the polymer may be a compound of the oxazole type, or a base film containing an aromatic dye compound), and (iv) a second conductive back film which would emit the residual thermal energy.

The maximum theoretical efficiency of 24 percent associated with single-crystal semiconductors may not apply to semiconductors made of organic-type materials. While *p-n* junction semiconductors can be made with organic compounds, other types of systems can also be developed, with charge mobilities and conductivities that do not depend upon single structure but depend, instead, upon the long-range intramolecular charge transfer in heavy molecules found in biological systems (for example, nerves). The semiconducting properties of such molecular systems may be very different in character from those of inorganic semiconductors, and hence may have no efficiency limitation. The major difference between the inorganic single-crystal semiconductors and the organic systems is that in the former the charge creation and motion are related to the primary act of light absorption whereas in high-molecular-weight organic systems there is a distinction between charge formation in a molecule and diffusion through the bulk medium. In the organic system the charge may be transferred within the molecule before motion to an adjacent molecule or vacancy site occurs (*11*). Thus, although the actual mechanisms of charge formation and transfer in organic semiconductors are not well understood, advantage can be taken of both the low-energy band gap of such materials and a possible low rate of thermal backward diffusion of charge.

Techniques now used in the production of plastics and phosphor for protection and for shifting wavelengths to lower energies could be developed to give protection against radiation damage that could lead to deterioration of organic materials exposed to the full range of solar and cosmic radiation.

The major promise of organic systems, therefore, is that they would have much higher efficiency than inorganic semiconductors, they would weigh less than inorganic systems, and they could be produced in large quantities at a much lower cost.

On the assumption of a conversion efficiency of 80 percent, a collector area of 8.7 square miles (equivalent to a circular area 3.3 miles in diameter) would be required to supply the power (2.5×10^7 kilowatts) that was needed to meet the power requirements of the northeastern United States in 1966. Such a collector would weigh 330,000 pounds, exclusive of supporting structures.

Design studies have already been made to explore the feasibility of constructing large arrays which could be deployed in space. For example, the de-

Table 3. Estimated area and weight of solar-collector surface needed to supply the demand for electrical energy shown in Table 1. [Estimates by Arthur D. Little, Inc.]

Region	Gallium arsenide*		Silicon †		Organic system,‡ 24% conversion efficiency		Organic system,‡ 80% conversion efficiency	
	Area (mi^2)	Weight (10^6 lb)	Area (mi^2)	Weight (10^6 lb)	Area (mi^2)	Weight (10^6 lb)	Area (mi^2)	Weight (10^9 lb)
				A.D. 1966				
World	1,170	4,930	700	1,190	440	16	132	5
United States	370	1,560	220	380	100	7	43	1.5
Northeastern U.S.	77	320	46	78	29	1	8.7	0.3
South Atlantic U.S.	70	300	47	80	26	0.9	7.9	.3
New York City	14	60	8	14	5	.2	1.6	.06
				A.D. 1980				
World	2,270	9,580	1,360	2,310	850	305	255	9.2
United States	960	4,040	580	980	360	13	108	4
Northeastern U.S.	180	740	105	180	66	2	20	0.7
South Atlantic U.S.	160	660	95	160	59	2	18	.6
New York City	130	120	16	28	10	0.4	3.2	.12
				A.D. 2000				
World	7,000–10,500	29,500–44,300	4,200–6,310	7,120–10,700	2,630–3,940	95–140	790–1,180	29–42
United States	3,155	13,300	1,890	3,210	1,180	43	350	13
Northeastern U.S.	420	1,780	250	430	160	5.6	47	1.7
South Atlantic U.S.	380	590	230	380	140	5.1	42	1.5
New York City	84	350	48	84	30	1.2	9.6	0.36

* Gallium arsenide: conversion efficiency, 9 percent; weight per unit surface area, 4213×10^3 lb/mi²; thickness, 5×10^{-3} inch. † Silicon conversion efficiency, 15 percent; weight per unit surface area, 1696×10^3 lb/mi²; thickness, 5×10^{-3} inch. ‡ Organic systems: conversion efficiency, 24 percent (maximum theoretical efficiency for inorganic single crystals) and 80 percent; weight per unit surface area, 36×10^3 lb/mi²; thickness, 0.25×10^{-3} inch.

sign of a large radio-astronomy antenna consisting of two satellites separated by a 6-mile adjustable-length tether has been evaluated (*12*). Because pointing accuracy for the solar-energy collector is not critical, attitude controls involving use of a gas-fueled reaction control system at the edges of the structure could be provided. Thermal and structural analyses of large flexible paraboloid antennas which may be subject to solar heating in a synchronous orbit have been carried out in an effort to evolve designs best suited for microwave transmission (*13*). These studies have been made for parabolas considerably larger than would be required for this particular purpose.

Power Generation and Transmission

Electrical interconnections between sectors of the solar-energy collector could provide power, in the range of hundreds of kilovolts, directly to a klystron traveling-wave amplifier. Amplifiers, of about 90-percent efficiency, with extremely high continuous-wave power outputs are close to realization. These amplifiers can be used to generate microwave radiation to transmit power (for example, 2.5×10^7 kilowatts) back to earth. For 10-centimeter wavelength, a transmitting dish antenna of about 2-kilometer diameter would irradiate an area about 3 kilometers in diameter to supply the power needs for a region such as the Northeast (Fig. 3). The radiating antenna would have to be carefully pointed by attitude control devices to obtain directional accuracy of the microwave beam. Advances in guidance mechanisms and past successes in pointing antennas to a predetermined area on the moon indicate that the required pointing accuracy can be achieved.

The power density would be less than 1 watt per square centimeter; this would produce a voltage gradient, when the microwaves pass through the upper atmosphere, of less than 100 volts per centimeter. At this voltage gradient, ionization of the atmosphere would be unlikely to occur. Also, through selection of the 10-centimeter wavelength, atmospheric absorption would be minimized if not eliminated.

It is likely that humans will be required for the deployment of a large structure such as a solar-energy collector and a microwave antenna. They would have to perform the functions of station keepers, equipment monitors, and maintenance. In the time frame within which the use of a complete system is considered, man's role in space will have advanced to a point where a prolonged stay in orbit will be commonplace.

Earth Receiving Station

In order to transmit 2×10^7 kilowatts of power to an earth receiving antenna 3 kilometers in diameter, the microwave beam would have a power density of less than 1 watt per square centimeter. This would be greater by an order of magnitude than the power density of the solar radiation received on earth. A dipole receiving field utilizing highly efficient solid-state rectifiers could be used to absorb this energy. The resulting power would then be fed into a distribution network through superconducting transmission lines. Such networks have already received considerable attention, and research is being performed, in this country and abroad, on this method of electrical power transmission (*14*).

Although the power densities in the microwave beam might damage objects or living tissues that entered the beam, they would not be high enough to cause major destruction. Safety devices would have to be devised and regulations established to prevent entry of objects or living beings into the beam. The problem of safety should be no more difficult than that of highway and air traffic control.

Conclusions

We should not underestimate the development efforts that will be required to construct, launch, and operate the suggested solar-power-generating satellite. At this time, solution of most of the difficulties is expected to be within the projected capabilities of systems engineering, and not to require the discovery or development of new physical principles. The developments required for such a system, or for other, competitive large-scale applications of solar-powered devices, are not far enough advanced to allow detailed cost-benefit analysis. However, the cost of such devices and of such power-generating plants can be estimated, and these costs should be evaluated and compared to the projected costs of nuclear power plants over the next two decades.

The search for power from the sun appears to be less of a technological gamble than it seemed when we first announced our objective of landing a man on the moon, and returning him to earth, by 1970. In fact, projects such as the development of solar power may prove to be a logical outgrowth of achievements in space, and may help lead the world into an era in which an abundance of power could free man from his dependence on fire.

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