X-760-71-135

PREPRINT

NASA TM X- 65497

THE GENERATION OF POLLUTION FREE ELECTRICAL POWER FROM SOLAR ENERGY

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MARCH 1971

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Projections of the U. S. electrical power demands over the next 30 years indicate that the U. S. could be in grave danger from power shortages, undesirable effluence and thermal pollution. A pollution free method of converting solar energy directly into electrical power using photovoltaics on the ground shows that sunlight falling on about 1% of the land area of the 48 states could provide the total electrical power requirements of the U. S. in the year 1990. By utilizing and further developing some NASA technology, a new source of electrical power will become available. Such a development is attractive from conservation, social, ecological, economic and political standpoints.

While the cost of producing solar arrays by today's methods prohibits their use for large scale terrestrial plants, the paper suggests how the cost may become acceptable, especially as conventional fuels become scarcer and more expensive.

Some of the desirable reasons for developing methods to convert solar energy to electrical power are: to conserve our fossil fuels for more sophisticated uses than just burning, to reduce atmospheric pollution by 20%, to convert low productive land areas into high productive land areas, to make the U. S. less dependent upon foreign sources of energy, and to learn to utilize our most abundant inexhaustable natural resource.

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INTRODUCTION

The rapid advancement in the American standard of living is reflected in the drastic increase in the nations electrical power demands. In 1938 the U. S. had an electrical power installed capacity of approximately 26 million kilowatts. Thirty years later (1968) there were 226 million kilowatts of capacity installed. [1] The actual installed capacity and the projected requirements [2] for the next twenty years are shown in Figure 1. Clearly, the electrical power demand across the U. S. is doubling every 10 years and in some areas, such as Washington, D. C., the requirements are doubling every 8 years.

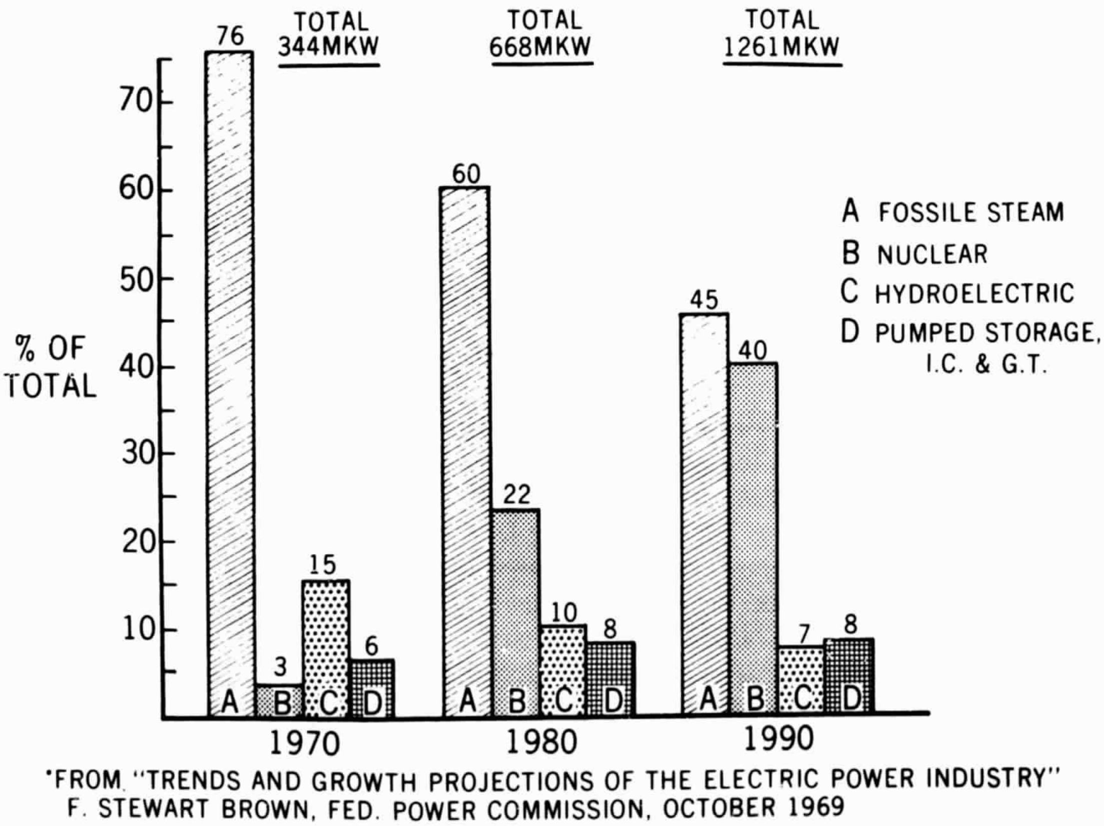

Figure 1-Electric Requirements and Supply for U. S.

Figure 1 shows that the principle method of power generation is the burning of fossil fuels and shall continue to be so for at least the next 20 years. Nuclear power generation is projected to increase from something around 3% today to about 40% of our needs by 1990. While hydroelectric installations represent about 15% of the U. S. capacity in 1970, they will account for only about 7% of the U. S. demand in 1990. The U. S. has run out of suitable sites for hydroelectric installations. Other conventional methods of power generation, such as internal combustion and gas turbine facilities, will probably play only an auxiliary or emergency power supply role.

Except for hydroelectric installations, the other means of generating power produce undesirable byproducts of CO_2, CO, nitrous oxides, SO_2, fly ash, water vapor and large amounts of waste heat which must be vented into the atmosphere or dumped into rivers or lakes. Since the best of the fossil and nuclear fueled installations are between 30% and 40% efficient, about 2 kilowatts of thermal energy must be dissipated for each kilowatt of electrical power generated. Also, the disposition of vast amounts of nuclear waste must be taken into account as this method of power generation becomes more and more prominent.

There are serious questions concerning the advisability of continuing to produce electrical power at the expense of our environment and the wholesale exploitation of our irreplaceable natural resources, such as natural gas, oil, coal and nuclear deposits. Perhaps the time has come for a reappraisal of other methods of generating electrical power if only to supplement our present methods so that the rate of increase in use of our irreplaceable natural resources will be slowed.

Non Conventional Methods of Producing Electrical Power

Examining other methods for generating electrical power requires the need to restrict it to processes which will not seriously affect the ecology. Tidal action might be harnessed in some regions of the U. S. and the World but this would be so restricted as to add little to the U. S. generating capacity. World wide potential generating capacity is estimated to be 64 MKW.[3] Wind power, in certain regions, has promise but in the heavily populated locations of the U. S. the velocity and consistency is highly variable. Geothermal power has interesting possibility and is particularly favorable in certain regions, especially along the west coast of the U. S. Some pilot plants are already in operation in the U. S. and other places in the world. About 0.8 MKW is installed and should reach 1.34 in 1971 world wide.[3] It is however, a polluting process in the sense that thermal energy is being removed from the earth's interior faster than by natural processes. Therefore extensive use of this method would introduce substantial amounts of heat into the surface environment.

Perhaps the most abundant source of energy available to man is solar energy. It is entering the earth's atmosphere at a density of 130 watts/ft^2 which means that over every square mile 3.6×10^6 kw potential energy is available during the sunlight hours. Solar energy is an absolutely clean "fuel", has no by products and for all practical purposes is inexhaustible. Its interception and partial conversion to electrical power would not cause thermal unbalance since the energy is arriving at the earth in any event.

Various methods of using solar energy for heating hot water, warming buildings, drying foods, recovery of salt and other chemicals, as well as agricultural processes, are well known. However, its direct conversion into electrical power has been restricted to outer space applications where over 90% of the U. S. unmanned space vehicles are solar powered. Photovoltaic, thermoelectric, thermionic and dynamic processes have been investigated as means of generating electrical power from sunlight in the U. S. space program, but the method which proved most practical was the photovoltaic (solar cells).

Let us now turn our attention to the consideration of using solar cell processes for conversion of solar energy into commercial quantities of electrical power.

Conversion of Solar Energy on the Ground

Figure 2 shows the WH/ft^2 of solar energy falling on a horizontal surface at 40°N latitude on the east coast of the U. S. under various seasonal and weather conditions. [4] The power available was considered when the solar illumination was sufficient to develop useful power in the array. At no time was there sufficient illumination on the cloudy winter day to generate significant power. Table 1 summarizes the total KWH available under the various conditions measured for a ground power station 1 mile square in size.

A fully electrically equipped modern 1750 ft^2 air conditioned home along the east coast of the U. S. averages about 1200 KWH per month from May through September to operate its electrical equipment. This same house in the October through April period requires about 700 KWH per month, exclusive of heating. Thus a square mile of solar array, as illustrated in Figure 3, during the summer months, assuming 60% sunshine hours at 7% conversion efficiency, could produce enough power to accommodate about 18,000 homes. This same power station during the winter months with about 50% sunshine hours and lower intensities could accommodate about 10,000 homes.

By providing an electrical storage system for the station as illustrated in Figure 3 around the clock power would be available. Using lead acid storage batteries similar to those installed in telephone exchanges, a storage capacity of 2.6 KWH/ft^3 can be obtained. A 1 million KWH storage capacity would require about 400,000 ft^3 or a building approximately 115 ft x 115 ft x 30 ft high. This storage could provide around the clock power to the 10,000 homes in the winter time for 4 full days, should this be necessary or it could be used to handle peak power demands.

The entire electrical power requirements for Washington, D. C. and Prince Georges County, Maryland (PEPCO) for 1969 were 1.1×10^{10} KWH/yr.[5]

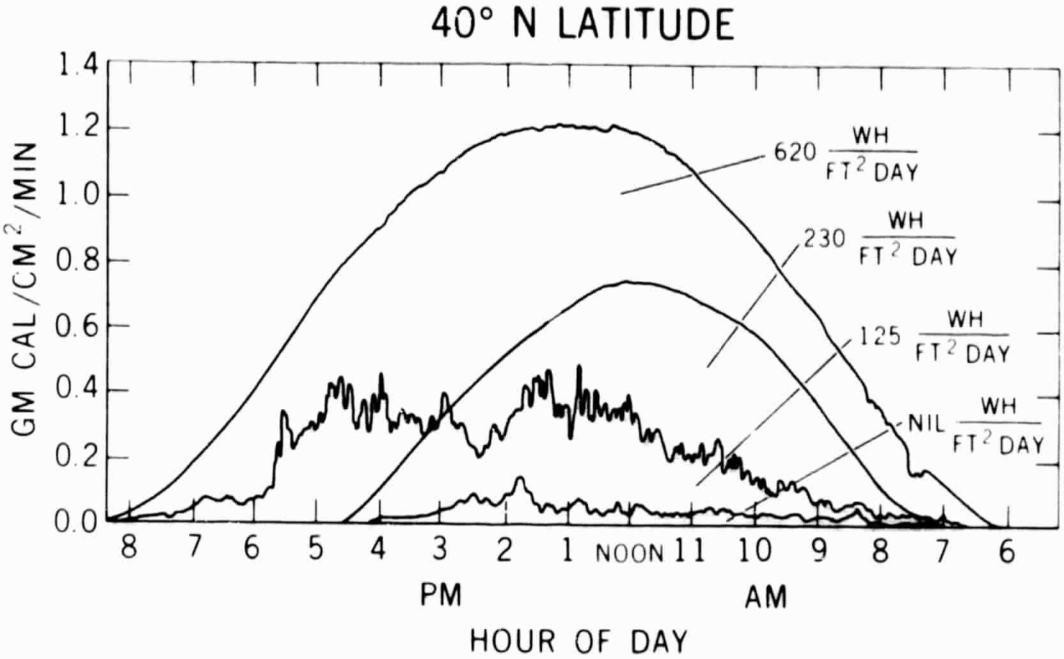

Figure 2-Solar Insolation at Sea Level on Various Days

Table 1

Incident Energy/Power Available, 40° N Latitude Sea Level

Season and Type of Day	Kilowatt Hours Per Square Mile Per Day			
	Incident Solar Energy	5% Conversion	7% Conversion	10% Conversion
Clear Summer Day	17.3×10^6	0.86×10^6	1.21×10^6	1.73×10^6
Clear Winter Day	6.5×10^6	0.32×10^6	0.45×10^6	0.65×10^6
Cloudy Summer Day	3.5×10^6	0.17×10^6	0.24×10^6	0.35×10^6
Cloudy Winter Day	NIL	NIL	NIL	NIL

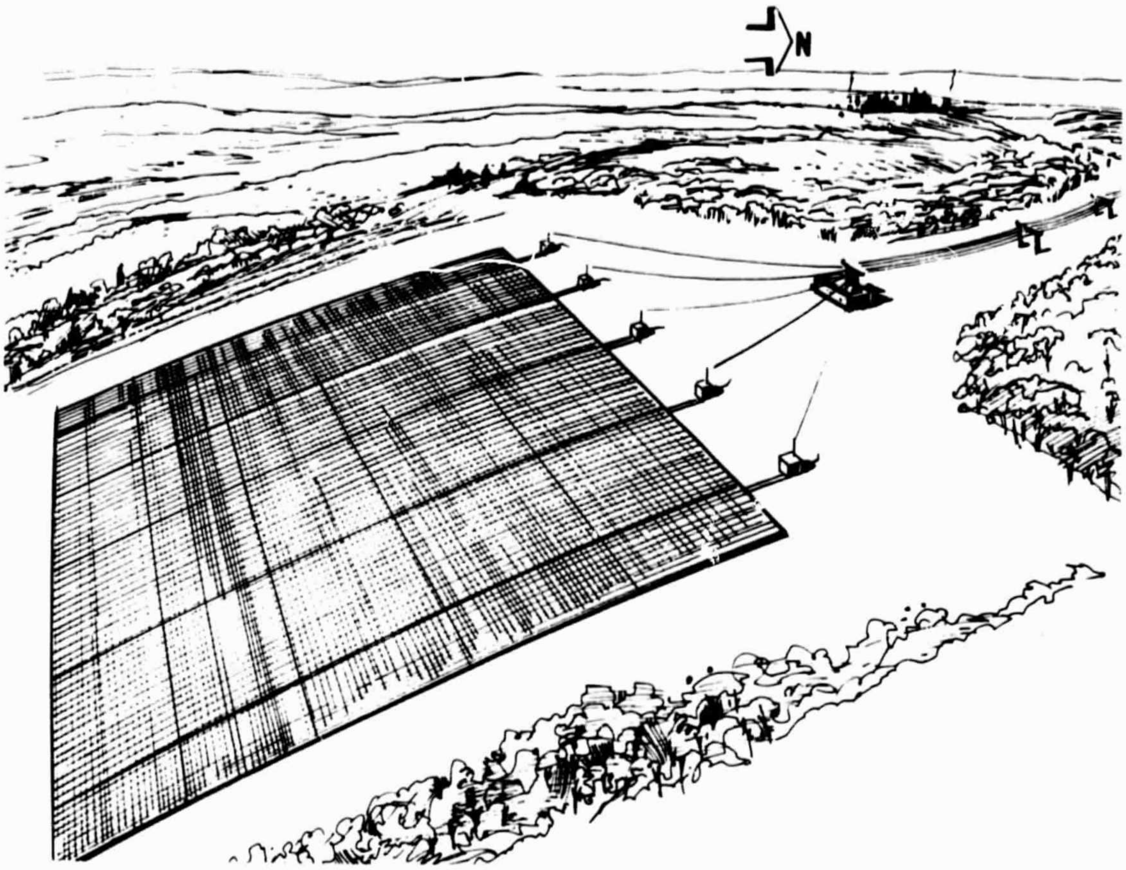

Figure 3-One Square Mile Terrestrial Solar Power Plant

Figure 4 shows the Mean Monthly Percentage of Possible Sunshine in various parts of the U. S. If a terrestrial solar power station was built in the Washington, D. C. area it would require an area of about 73 square miles to produce PEPCO's 1969 needs. The total area serviced by PEPCO is about 545 square miles so it requires about 1 square mile to service about 7.5 square miles in the Washington, D. C. area.

It the same power station was located in the sunny S. W. U. S. where the possible sunshine hours average nearly 70% year around, then PEPCO's needs could be generated in a region of about 53 square miles.

Enormous land areas in the arid parts of the U. S. are low productive regions. Many thousands of square miles, could be made highly productive, "harvesting a crop" of electrical power for sale in the areas where it is vitally needed. Not only would the land become more productive and valuable but the U. S. would become less dependent upon foreign import of energy resources. Considerable

Figure 4-Mean Monthly Percentage of Possible Sunshine for Selected Stations

savings of our irreplaceable natural fuels could be made and a big step toward relief from atmospheric and thermal pollution would be accomplished.

It is estimated that the total U. S. electrical power needs for 1990 will amount to some 6.6×10^{12} KWH/yr. Assuming the 7% conversion efficiency as before and 70% sunshine hours in the SW U. S. about 31,500 square miles of solar array could generate our nations total needs. This represents barely 1% of the land area of the 48 states.

If ways could be found to intercept the solar energy entering our upper atmosphere(6), then over 3 MKWH of power could be generated during the summer months and over 2 MKWH during the winter each and every day from a 1 square mile station. To provide the annual consumption of Washington, D. C and Prince Georges County, Maryland it would require about 15 square miles of array at 80% transmission efficiency. While such a station would be above the weather and benefit from 100% possible sunshine hours every day, there are major problems to be overcome in supporting such a power station and of transmitting the power to the ground.

The ultimate method of generating vast quantities of electrical power would be from a series of synchronous satellites(7) illustrated in Figure 5 beaming the

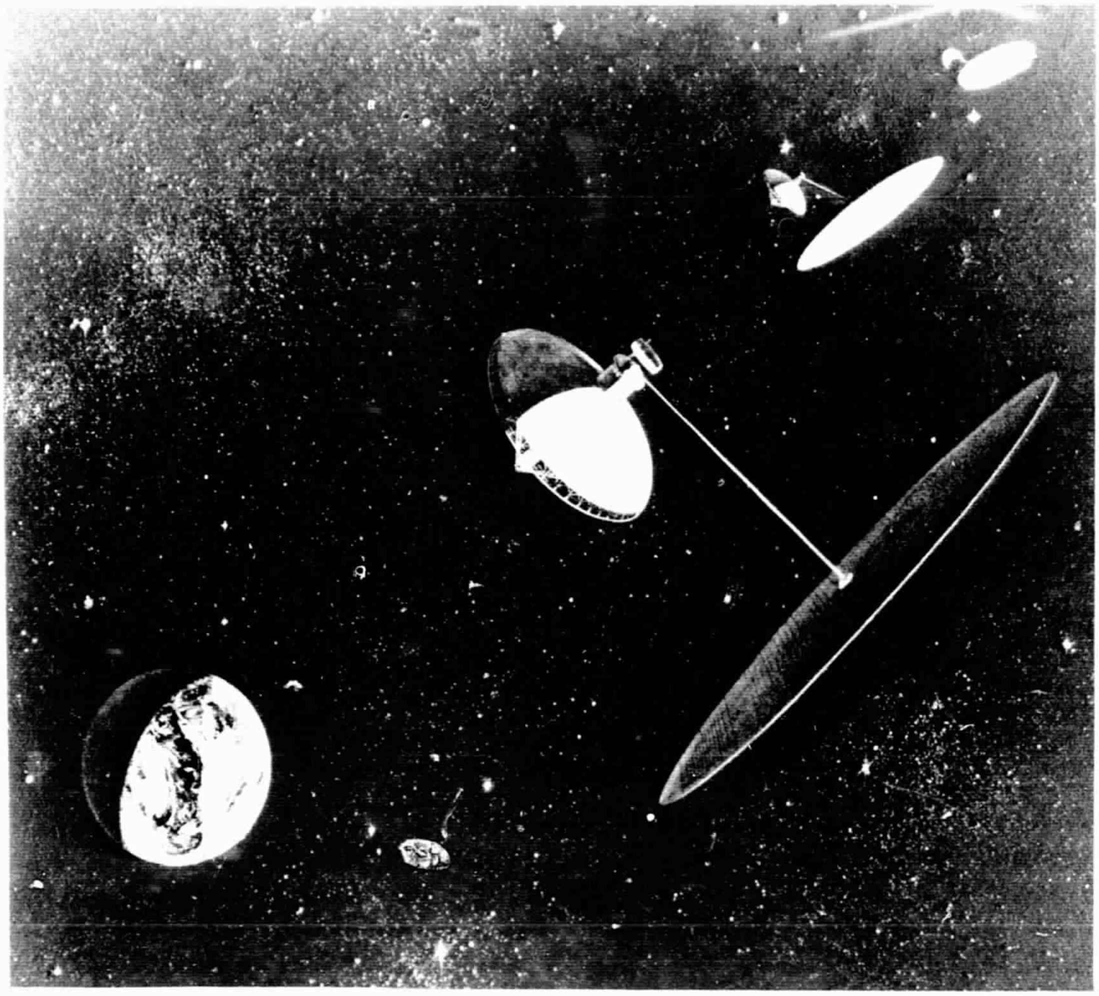

Figure 5. Solar Power Satellite Station

microwave power back to earth to be used wherever needed. A satellite with an area of about 6-1/4 square miles could generate the total power requirements of Washington, D. C. and P. G. County, Maryland. The losses of converting the DC power to microwave frequencies, transmitting through 22,300 miles and re-converting to useful power on the ground are considered to be 20%. Table 2 summarizes this comparison.

Conventional Electrical Power Costs

Most commercial power stations are amortized over a 20 year period. Typical cost of generating 1 million KW of electrical power for 20 years by conventional

Table 2

Comparison of Solar Power Generation on the Ground, Upper Atmosphere and in Synchronous Orbit

Assuming 7% Conversion Efficiency

Location & Condition	Area to Provide Pepco Production 1.1×10^{10} KWH/YR (1969) Square Miles	Area to Provide Total U. S. Requirements 6.6×10^{12} KWH/YR (1990) Square Miles	Area Ratio
Ground, Wash. D. C. 50% Sun	73	---	11.7
Ground, S. W. U. S. 70% Sun	53	31,500	8.5
Upper Atmosphere 100% Sun 80% Transmission Eff.	15	8,900	2.4
Synchronous Orbit 100% Sun 80% Transmission Eff.	6-1/4	3,700	1

methods(8) are shown in Table 3. The least expensive method obviously, is hydroelectric where most of the cost is tied up in the installation. The wide variation of cost, ranging from $170-$590 per installed KW is related to location, where some may be in rugged isolated terrain and require the relocation of roads, railroads and towns. The big advantage of hydroelectric installation is the zero "fuel" cost.

Natural gas is the cleanest and at present least expensive type of fossile fuel generating plant. It is also the first fuel which is likely to be depleted since these reserves are indeed seriously limited. At present it costs about $463 per installed KW to build, maintain and operate a plant for 20 years at 1968 prices. Perhaps manufactured gas can be produced from coal or shale but it will cost more than natural gas.

Oil and coal fired installations are quite comparable in cost, ranging from about $516 to $534 per installed KW, and they will probably be the major fossil fuels used to generate electrical power for the rest of the century. No charges for the deterioration to our environment are accounted for in the costs shown in Table 3.

Table 3

20 Year Cost of Installation, Maintenance and Fuel for Power Stations (1968)*
1 Million KW Installation

Type	In Millions of Dollars			
	Installation	Non Fuel	Fuel	Total
Hydroelectric	150-470	20-120	-	170-590
Gas Fired	150	32	281	463
Oil Fired	175	57	284	516
Coal Fired	100	47	387	534
Nuclear Fueled	200	152	301	653

*Based on FPC November 1969 "Hydroelectric & Steam Power Plant Construction and Annual Production Expenses" Report.

It still costs about 1-1/2 times as much to generate electrical power with nuclear energy than with natural gas, but as the fossil fuels become less abundant and more expensive to retrieve, it is expected that the fossil and nuclear fueled plants will cost about the same to operate.

Solar Electrical Power Costs

Today the direct conversion of solar energy into electricity is very expensive and confined to those applications where conventional processes are impractical. Solar cells have found wide application on long life unmanned spacecraft. The solar cells manufactured for the space program are subjected to stringent specifications and high quality control measures, both of which involve expensive hand operations. Further, the demand for solar cells is quite small amounting to some 2 million devices per year with a total market value of between 6 and 8 million dollars. Also the demand is sporadic.

This involves numerous start-ups and shutdowns of the production line, resulting in considerable waste in manpower and materials. Finally, no standard design has been agreed upon by the users, forcing the manufacturers to rely heavily on many hand operations simply because it is economically unfeasible to invest in automation.

Because of all this, oriented space solar arrays, like the large Apollo Telescope Mount illustrated in Figure 6, cost about $2,000,000 per KW. A recent study[9]

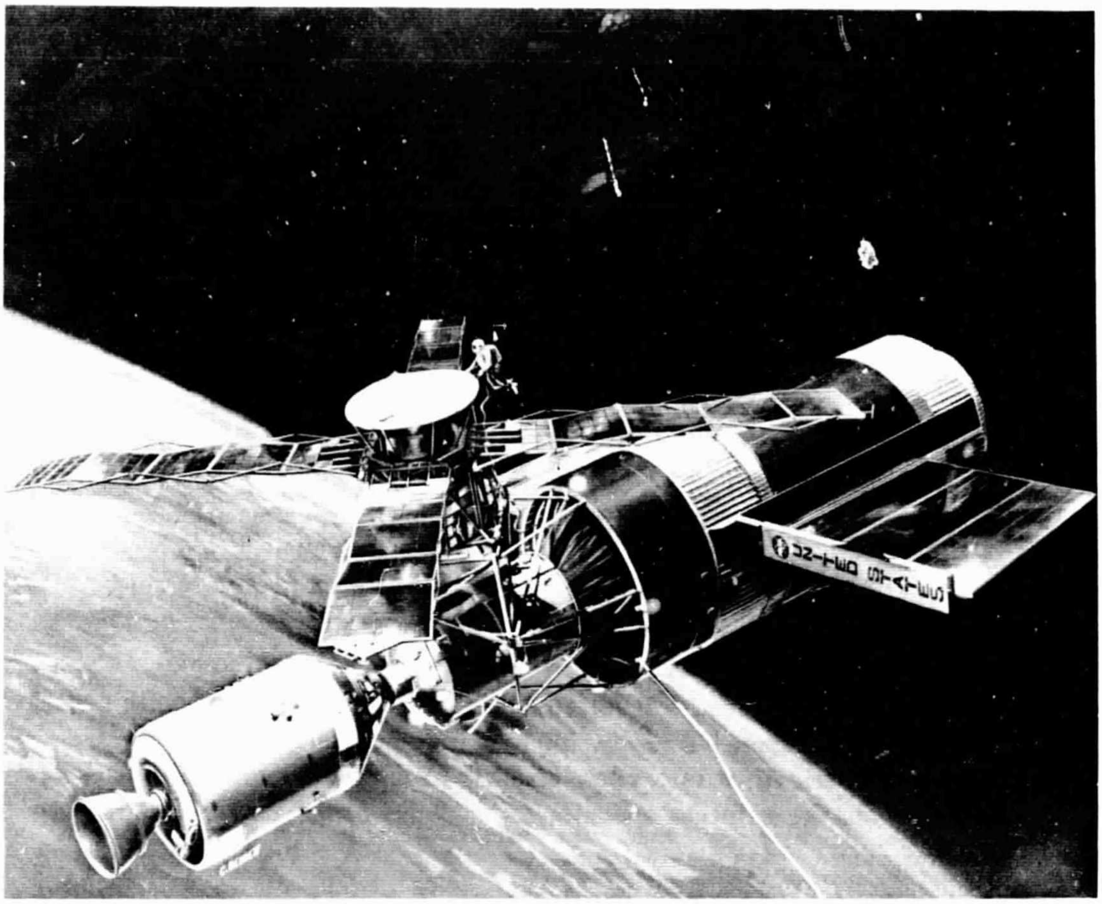

Figure 6. Apollo Telescope Mount with Space Station

has shown that cells for terrestrial applications can be made now for about $15,000 per KW using existing silicon solar cell manufacturing methods, by relaxing the stringent space cosmetic and performance specifications, changing the cells' shape for better utilization of the single crystal silicon, and automating many of the processes for large scale production. By using simple concentrators, as illustrated in Figure 7, which would require fewer cells to generate the same electrical power, the cost would be nearer to $10,000 per KW.

The next big step in cost reduction would be the utilization of inherently inexpensive processes, such as evaporation or deposition on long sheets of substrate. Thin film solar cells made of cadmium sulphide in 3" x 3" sizes are in pilot production now and might be mass produced for $2,500 KW.

Figure 8 illustrates a process where many thousands of square feet of solar array might be produced at costs around $50 per KW under space simulated

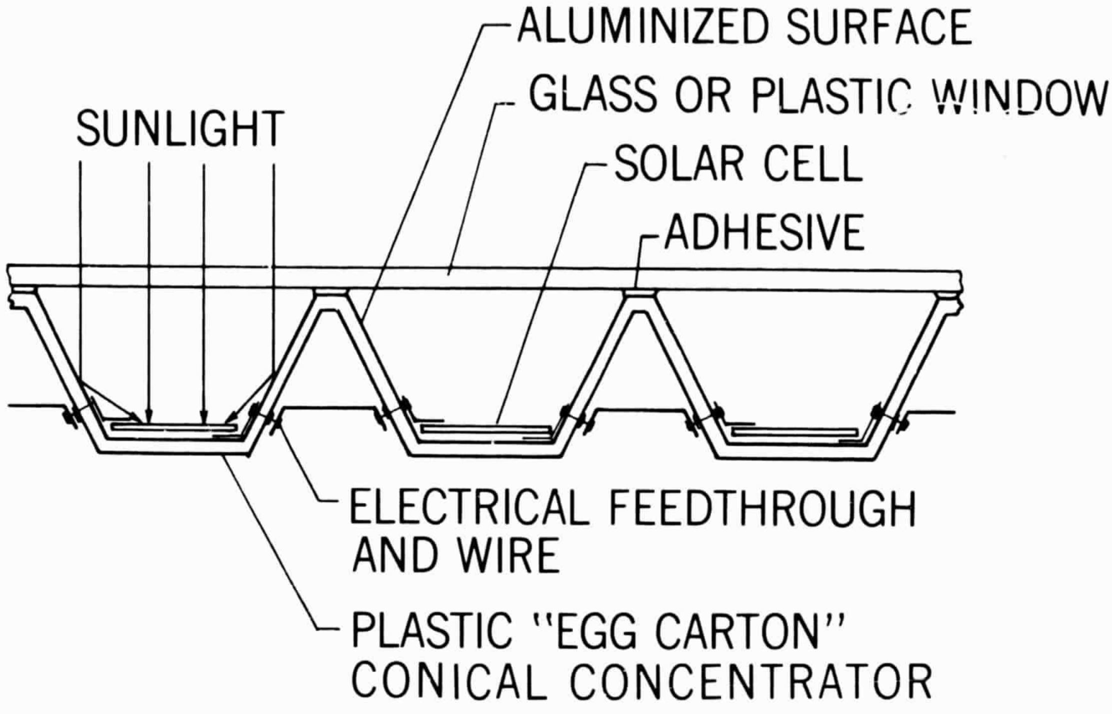

Figure 7-"Egg Carton" Concentrator Design

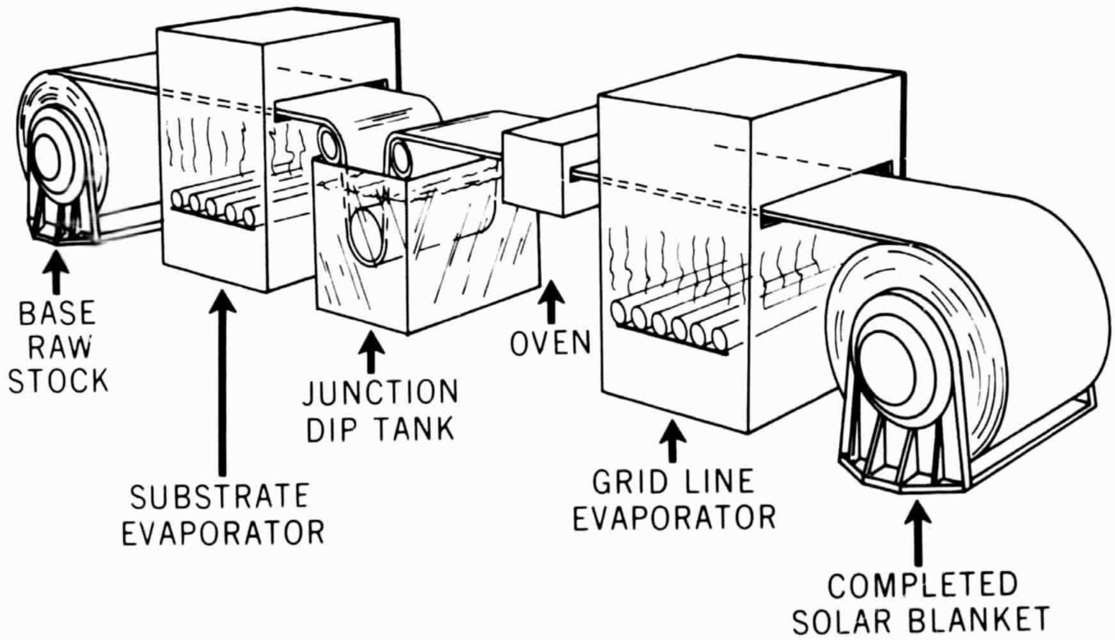

Figure 8-Solar Array Manufacturing

conditions or \$.50 per square foot. Thus a square mile of array would cost about \$14 million. Construction of the necessary ground support structure and conductor might amount to \$1.00 per square foot or \$28 million per square mile. Batteries for a 1,000,000 KWH storage facility might cost \$10 per KWH or \$10 million when purchased in large quantities, and the necessary buildings and switching gear might add another \$20 million over a 20 year period, including two battery replacements.

Since the solar array is a direct energy conversion system and has no fuel costs associated with it, its operating costs should be considerably less than any of the dynamic systems; perhaps as low as \$1.00/ft^2 over 20 years or \$28 million per square mile which would include 2 array replacements. Table 4 shows that a 1 square mile solar array power station, built after techniques are developed to produce low cost solar arrays and batteries, would cost about \$100 million to build, operate and maintain over a 20 year period. A solar array in the sunny S. W. part of the U. S., using a 70% sunshine factor, would generate at least 2.1×10^8 KWH/mi^2yr. If the power were sold for 3¢/KWH, about twice today's rates, the gross return over a 20 year period would be $\$1.26 \times 10^8/mi^2$. Subtracting the installation, maintenance and operating costs of $\$1.0 \times 10^8/mi^2$ leaves about \$26 million net income per square mile over 20 years. This land is then producing a "crop" which yields about \$2,000 per acre per year. Farm land yielding such a net return is considered premium.

Major Problems to be Solved

Before the large scale terrestrial use of solar energy to generate electrical power can take place, the cost of solar arrays must be reduced in cost between

Table 4

Cost of 1 Square Mile Solar Array Power Station

Solar Array @ \$0.50/Ft^2	$\$14 \times 10^6$
Site Construction	$\$28 \times 10^6$
Storage and Switching Facility	$\$10 \times 10^6$
Maintenance of Storage Facility (2 Replacements in 20 Years)	$\$20 \times 10^6$
Maintenance and Operation of Station (2 Array Replacements in 20 Years)	$\$28 \times 10^6$
Total 20 Years Construction Maintenance and Operating	$\$100 \times 10^6$

3 and 4 orders of magnitude. The unautomated jewelry techniques presently used for making solar cells must be replaced by massive automated techniques using abundant low cost materials.

Instead of the 7% efficient arrays considered in this paper there is definite promise of doubling this performance within the next 5 to 7 years by improving the solar cell material and better controlling the process.

Methods of constructing large area arrays on the ground from materials that can withstand many years of sunlight and weather must be developed. Large scale production of UV resistant plastic sheets, for example, would be required.

Development of large scale batteries, capable of long life and deep cycles, is needed to solve the 24 hour per day requirement. While the batteries will be operated at an ideal environment condition, they must have high storage density and be made of abundant and inexpensive materials. They should be constructed from materials that, after being formed, can be reprocessed time and again so as to eliminate the need for complete replacement of materials.

Reasons for Converting Solar Energy into Electrical Power

Following are some reasons why development should be started immediately on the conversion of solar energy to electrical power:

a. To conserve our irreplaceable natural resources such as gas, oil, coal and nuclear ore so they can be used for more valuable purposes than just burning.

b. To make, considerable progress toward reducing atmospheric and thermal pollution which are having serious detrimental effects on our environment.

c. To make many thousands of acres of our sun rich land more productive and valuable in producing a marketable "crop" of electrical energy.

d. To make the U. S. less dependent upon foreign sources of energy.

e. To learn to utilize our most abundant and inexhaustible natural resource, solar energy.

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