in the United States and that it is considerably less than the area covered by roads and highways.

There are three general kinds of photovoltaic power generation systems which have been under study. It would be useful to explore how each of them relates to the area problem. The first of these would be based on covering roofs of existing or newly constructed buildings with solar cells, or with combined solar cell and solar thermal energy collection units [1] (Figs. 2 and 3).[2] An important argument in favor of this type of system is that it would reduce the demands on power distribution networks since electric power would be generated at the consumption site. The second kind of system is the central power station system which would require covering areas of the order of square miles [2]. (A central station of 1 mi^2 area would have an average daily power generation capability comparable to that of a 100 Mw central station.) Such generating stations would probably be dedicated to some sort of plant. This mode of solar energy utilization evokes an image of high electric energy consuming plants (e.g., aluminum plants) being sited in sunshine-rich desert areas rather than near large hydroelectric installations as they now are. The third system is based on the concept of earth satellite central stations, transmitting power generated by solar cells to earth via microwave beams [3] (Fig. 4). Instead of covering large areas of the earth with solar cells, this system would require covering equally large areas with much higher efficiency microwave converters. The system has the advantage that the solar cells on a synchronous satellite would be exposed to the sun 24 hr a day and they could therefore deliver power on demand; i.e., no energy storage would be necessary. Furthermore, the total daily kwh/m^2 of microwave receivers would be about eight times what would be produced by solar cells covering the same area (the solar energy input to a satellite is a factor of 1.4 times the input at the earth's surface; the satellite generates power 24 hr/day compared to an average 4 hr/day for a surface system, which results in additional factor of 6).

From this brief discussion, it is reasonable to conclude that the area required for large scale solar energy conversion via the photovoltaic effect is not unacceptably large.

Energy Storage

As we have already pointed out, in the case of the satellite solar photovoltaic system, no energy storage is required: the system would produce power on demand. In the case of the other two systems, storage would have to be available for the 10 to 14 hours of night and day long periods of overcast skies, periods of rain and snowfall, etc. Unfortunately, the technology of large scale energy storage is relatively undeveloped, at least in part because traditional methods of generating electricity do not require such storage (energy is stored in fossil or nuclear fuels used in the generating station).

It is of interest to examine how solar energy is stored in nature. Photosynthesis occurs only while the sun is shining; the energy is stored in the form of chemical energy in the products of photosynthesis. Much of man's use of electrical energy results in the manufacture of products, be they metals, chemicals, machines, etc. If we devised manufacturing processes in which the plant would operate when solar energy was available, we could harvest the energy by collecting the product of the plant, not on a continuous basis, but rather by integrating over more extended periods of time. Such a manufacturing procedure would require basic changes in the organization of industry. Manufacturing, like agriculture, would operate not on demand, but rather in rhythm with a natural phenomenon; i.e., sunlight.

In general, however, the photovoltaic solar system will be expected to conform to the performance pattern of the current fossil fuel and nuclear generating stations, and it will require an energy storage system. There are a number of such possible energy storage mechanisms which might satisfy the requirements. These include electrochemical storage batteries, hydropump storage, storage in rotating masses, and storage in the form of hydrogen gas.

Electrochemical Storage. Consider generation of electrical energy by solar cells deployed on roof tops. It turns out that a house with a 2000 ft^2 roof area could store energy equivalent to the electrical energy it would produce on its roof during five clear days via 10 percent solar cells in about 50 ft^3 of commercial lead-acid storage batteries. Such batteries would cost about $600.00. Neither the volume required nor the cost are unreasonable. However, if lead-acid batteries were supposed to store a substantial fraction of all the electrical energy produced in the United States, it is questionable whether enough lead would be available. There are, of course, many other electrochemical systems, some of them based on abundant, inexpensive elements, and research in this area could lead to a solution of the energy storage problem.

Hydropump Storage. This involves using electric energy when available to pump water into reservoirs and extracting the stored potential energy on demand by allowing the water to flow back down through turbine generators. Such storage systems are already in use on a limited scale as a load leveling mechanism with existing generator stations. Objections are being raised, however, against the construction of the artificial reservoirs required for hydropump storage because they result in the flooding of large land areas. Furthermore, the number of sites suitable for large scale hydropump storage is limited. Consequently, hydropump storage would probably not solve all of the storage problems associated with large scale solar cell generation of electrical power.

Storage in Rotating Masses. The energy could be stored in the form of mechanical energy of a rotating

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[2] Numbers in brackets designate References at end of article.

mass. In this case, a motor-generator is operated as a motor when excess electrical power is available and it sets a "flywheel" in rotation, ultimately at very high speeds. Energy is extracted by allowing the rotating mass to drive the motor-generator as a generator. The system is, therefore, analagous to hydropump storage.

High density energy storage would require specially shaped flywheels composed of very high strength material capable of tolerating the high stresses which would develop at the extremely high speeds encountered in operation. No large scale use has ever been made of such flywheel energy storage; considerable research and development would be needed before wide scale application could become possible.

Storage in the Form of Hydrogen Gas. Recent studies of the possibility of energy storage in the form of hydrogen gas suggest that this could provide a solution to the problem. The hydrogen would be produced by electrolysis of water, an inherently very efficient process. The hydrogen could then be distributed from the central station via pipelines or perhaps in the form of liquid hydrogen. The energy could be recovered from the hydrogen through fuel cells which are very efficient converters. There are, of course, safety problems associated with the use of hydrogen and perhaps using the hydrogen to produce more easily handled compounds might be a preferred solution to the problem. Hydrogen as the energy storage medium is relatively unexplored, and again research and development must be expended to determine its full potential.

In summary, there are a number of large-scale energy storage methods which could potentially satisfy the requirements arising from large-scale solar cell electric power generation systems.

Costs of Conversion Systems

The most serious impediment to large scale photovoltaic solar energy conversion lies in the cost of currently available reliable, long-life, acceptable efficiency (>5 percent) solar cells. Although the photovoltaic effect is very commonly encountered in semiconductors, there are only two different semiconductor solar cell systems which are at a level of development sufficient to allow a credible analysis of their potential cost to be conducted. One of these is based on the single crystal silicon solar cell referred to initially; the other is based on the thin film cadmium sulfide cell. Each falls short of meeting the requirements for large scale solar energy conversion systems, though for different reasons.

The silicon cell is reliable, long-lived, and has a respectable solar energy conversion efficiency in excess of 10 percent. The only significant application for silicon solar cells has been supplying on-board electric power for unmanned space satellites. This involves a very small total power generating capacity, of the order of 50 kw peak power generation capability added per annum. The current cost of silicon cell arrays determined by this market is about $7000/m². In a recent analysis of the allowable costs of solar arrays intended for various applications, Wolf [1] concluded that the maximum allowable cost of solar arrays intended for central station power supplies is about $2.30/m²; for solar cell systems deployed on roof tops of buildings, $3.00/m²; and for solar cells to be deployed in a space central station system, $45.00/m². A reduction in cost should occur if the market were to expand from the current level of peak power production capability of 50 kw/annum to levels in the vicinity of tens of millions of kw/annum required to make a significant impact on the national energy budget. However, while a cost reduction by a factor of 100 seems attainable by making currently conceivable changes in production process, it is not evident that silicon systems based on current concepts can ever reach cost levels in the $2.00 to $3.00/m² level [2]. Examination of the added cost contributed at each stage in the manufacturing process indicates that the principal cause of the high cost is the need to make single crystals.

It is for this reason that the thin film CdS cell is attractive. The active part of this solar cell is a thin (10μ) polycrystalline film of CdS onto which an even thinner (0.1μ) layer of a copper sulfur compound film is grown. Recently, the Dupont Co. estimated that large areas of this kind of cell could be made for costs in the vicinity of $5.00/m² [4]. However, the current level of understanding of the photovoltaic effect in this system is not good enough to lead to the controllable fabrication of reliable, long-lived cells from CdS. Furthermore, their efficiency is in the vicinity of 5 percent, and it is not clear that it can be increased to levels comparable to those achieved in silicon.

Thus, with respect to cost of solar arrays, further research and development are required before it can be ascertained whether the cost levels required for large scale photovoltaic solar energy conversion are economically feasible.

Summary

In this article we have examined three objections commonly raised against the feasibility of large-scale generation of electric power by converting sunlight into electricity with the help of solar cells. It was concluded that the area needed for such power generation is not unreasonable; that methods of energy storage are available, and that there is reason for optimism with respect to reducing the cost for large-scale power generation from sunlight.

References

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