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PHOTOVOLTAIC POWER FOR TELECOMMUNICATIONS*

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Summary

Photovoltaic equipment may be an attractive power source for many kinds of communication equipment in the next five years. The first applications will be found in remote parts of the U.S. and in new systems installed overseas in areas remote from electric distribution grids. By the end of the 1980s, the equipment may compare favorably with grid electricity in some regions. This paper will discuss the kinds of improvements in equipment performance and manufacturing techniques which may lead to photovoltaic systems capable of competing in the communications industry; and estimate the cost of power which could be obtained if such improvements are achieved. It will review some of the problems of system design which must be confronted in constructing systems capable of meeting realistic demand patterns, and outline a technique for optimizing the size of components.

Introduction

The communications industry may provide one of the first major markets for electricity generated from solar energy; several hundred communications units are presently operating from solar power. Radio and microwave repeater facilities are frequently located in areas distant from electric transmission lines, and power must be provided to these facilities either from an onsite generating facility (*e.g.*, a system using diesel engines) or from a dedicated electrical transmission line. The cost of energy from either approach can be more than a dollar per kilowatt hour. In many cases these prices can be matched by solar electric systems (wind power, engines operating from solar heated fluids, and photovoltaic apparatus) already on the market or which should soon be on the market.

Photovoltaic systems are particularly attractive for remote electronic installations. Properly designed systems should be extremely reliable; barring acts of vandalism, maintenance should be limited to occasional servicing of the batteries and possibly cleaning the array surfaces. The photovoltaic arrays themselves should last more than twenty years. Since the systems do not involve any specialized mechanical equipment, it should be possible for

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a single crew to maintain and service both the power source and the communications equipment. The onsite solar systems have the additional advantage of being modular and can easily be expanded or reconfigured to meet new energy demands; conventional systems are typically designed with overcapacity in anticipation of future expansion [1].

It is likely that most of the solar powered communications equipment installed during the next few years will be small units operating overseas. Many developing nations are expanding communications networks into areas not well serviced by electric distribution systems, while most large facilities in the U.S. are located near an electricity grid. It has been estimated that only 10 - 20% of the microwave repeater stations in the U.S. are not attached to a transmission grid, while nearly half of the foreign installations do not use grid electricity [2]. Moreover, electricity from many utility grids in less industrialized nations can be extremely expensive and unreliable. In Africa, for example, electricity prices can be more than 15 c/kW h even in large cities [3]. In the countryside prices can be even higher and services may not be available 24 hours per day. In very remote areas solar equipment has the advantage of being relatively independent of a supply route. There is no need to bring in fuel, oil, and replacement parts to keep the system operating. The fact that the systems do not rely on imported petroleum will also be attractive in most areas. While reliable statistics are not available, it has been estimated that there are now 400 - 500 radio repeater stations outside the U.S. powered by photovoltaic equipment and 150 - 200 microwave facilities [4].

Photovoltaic technology

The major barrier to the use of photovoltaic systems is the high cost of the solid state component used to convert photons to electricity. The majority of the photovoltaic arrays now on the market are manufactured from single crystals of silicon. These arrays can be purchased for about $10 - 15 per peak watt of output. Prices, however, have been falling rapidly as private and federal funds have been directed to improvements in manufacturing techniques. The photovoltaic program in the Department of Energy has a goal of reducing array selling prices to fifty cents per peak watt of output (1975 dollars) by 1986 and to 10 - 30 cents by the end of the century [5]. This goal was established somewhat arbitrarily in 1974, but after four years of research, DOE's Division of Solar Energy still maintains that the goal can be met without any unanticipated "research breakthrough" (although such a breakthrough would obviously be welcomed).

There are three basic approaches to reducing costs: (1) refining the techniques now used to manufacture silicon cells; (2) develop "thin-films" of materials such as the CdS/Cu_2S junction, with reasonable efficiencies (*e.g.*, greater than 10%); (3) use optical equipment to concentrate sunlight on a high efficiency photovoltaic converter. It seems technically possible to reach the goal of 50c per peak watt with all three approaches [6].

(a) Silicon cells

Silicon cells are currently manufactured in much the same way that cells were made for spacecraft during the 1960s. Economies of scale and the introduction of some automated equipment have resulted in lower costs, but much work is still done by hand. Reaching the goal of 50c/Watt will require significant cost reductions in a number of different areas:

The silicon feedstock which now costs about 60 $/kg and contributes about $2.70 to the cost of cells, must be produced for about 10 $/kg, and the amount of material wasted in processing must be reduced. Several technologies which should make such cost reductions possible have been examined in the laboratory and are ready to be tested in pilot plants.

The batch method of Czochralski crystal growing must be replaced with a continuous process or a novel system for growing a ribbon or sheet of silicon crystal directly from the feedstock. Several promising approaches are now ready for prototype demonstrations. It may be possible to combine silicon refining with the growth of crystalline material. Techniques for growing ribbons or sheets of silicon can also eliminate the need to saw a silicon ingot.

The cost of converting a sheet of silicon into a photovoltaic cell by forming junctions and applying contacts and anti-reflective coatings must be reduced from the present cost of about $4 per peak watt to 15 - 25 cents per peak watt.

The cost of encapsulating the cells in a weatherproof array must be reduced by approximately a factor of 20.

(b) Thin films

A number of materials with high light absorptivities can be used to create photovoltaic junctions without the need to grow large single crystals (or large grained polycrystalline materials), as is the case with silicon. These devices typically employ a heterojunction in which two dissimilar materials such as CdS and Cu_2S are joined to produce the needed photovoltaic junction, a Schottky junction in which a semiconductor is joined directly to a metal contact, or "Metal, Insulator, Semiconductor" (MIS) junctions. The primary advantage of thin film cells is that it may be possible to produce them at very low cost by continuous spraying or some technique for applying a semiconductor material to a glass or metal substrate in a continuous process. The major present difficulty with such approaches is the relatively low efficiency of the cells produced. Low efficiencies present a serious problem since the costs of shipping and mounting photovoltaic arrays (costs which can exceed the cost of the cells themselves) are direct functions of the area of the arrays and, thus, inversely proportional to efficiency. It seems possible, however, that thin film cells using CdS and other materials can be manufactured with efficiencies greater than 10%.

Cells based on an amorphous "alloy" of hydrogen and silicon offer particularly intriguing possibilities. If perfected, these cells could combine the advantage of the silicon material (which is stable, nontoxic and plentiful) and thin-film manufacturing techniques. Unfortunately, it has proved difficult to improve the efficiency of such devices (presently 5.5%) and to increase the size of cells without sacrificing performance.

(c) Concentrating systems

If an optical device focuses sunlight on a photovoltaic cell, the area of active photovoltaic material required for a given level of output can be reduced roughly by the magnification of the optical system multiplied by the optical efficiency of the surfaces. Concentration ratios of 20 - 30 can easily be achieved with devices which track the sun by moving about a single north–south or east–west axis and concentrations of 500 or more can be achieved with two-axis tracking. In such systems, the bulk of the cost of the unit is attributable to the device itself. While some progress can be clearly made in reducing the cost of the tracking units, research on cell performance will be critical to the success of these systems. Since only a small amount of cell material is required, it is possible to make a substantial investment in improving the performance of cells used. Improving the performance of the cell, of course, translates directly into a reduction in overall efficiency. It seems possible to design silicon cells for use in concentrators with efficiencies greater than 20%. Cells with efficiencies as high as 28% have been constructed [7]. It is theoretically possible to develop cells with efficiencies of more than 35% using multi-junction cells or thermo-photovoltaic devices.

Concentrator systems can maintain better angles with respect to the sun, but can only use direct sunlight (diffuse sunlight is not concentrated). The fact that the concentrators have moving parts has been a major barrier to the use of these devices in remote, unattended communications facilities. Manufacturers of such systems point out, however, that the systems only execute a single rotation per day and certainly have far fewer moving parts than the diesel generators they would be designed to replace. More field experience will clearly be required to be convincing on this point. Several ingenious techniques have been proposed for achieving some concentration without moving parts. Simple, compound parabolic surfaces, for example, can provide concentrations of 2 - 4 without tracking, and an ingenious scheme using a flat plastic sheet impregnated with fluorescent dye is being investigated.

(d) Balance of system costs

While the photovoltaic cells (or cells and tracking units) now represent the bulk of photovoltaic system costs, other aspects of system costs are becoming important as cell costs are reduced. In the case of communications, this equipment can be extremely simple: a prepared site with appropriate footings, a simple frame, a power regulator to control the charging and discharging of batteries, the battery storage equipment itself, and miscellaneous wiring and interconnection. In new applications, systems engineering costs can also be significant. Present costs can be as high as 10 - 20 dollars per peak watt, but these costs can be expected to fall as modular systems are developed [8].

One of the few places where real technical progress may be made is in the area of battery storage systems. Nearly all present installations are lead–acid battery systems specially designed to operate with numerous deep discharges. The batteries with a sheltering structure can cost 60 - 120 $/kW h, adding 10 - 15 dollars per peak watt in a stand-alone facility in a good climate. Research is underway on a number of advanced battery systems, however, and it may be possible to achieve significant savings in storage cost by the mid-1980s [9].

System design strategies

With this brief background on the basic characteristics of photovoltaic equipment it is possible to examine some of the considerations which must enter an analysis of a complete photovoltaic powered communication system. In undertaking such an analysis it is necessary to recognize the uniqueness of the solar energy source; a number of considerations enter the system design which need not enter the analysis of conventionally powered systems.

Communications equipment does not provide a particularly attractive load profile for photovoltaic systems since most modern digital systems exhibit a relatively constant load. Photovoltaic systems clearly are better suited to loads which peak during the daylight hours. In some kinds of systems air conditioning equipment used to cool the electronics have peaks during sunny periods. One advantage of telecommunications loads, however, is that they can use the direct current available from the photovoltaic systems and storage batteries; a relatively inexpensive power conditioner can be used as an interface. Air-conditioners can be built with direct current motors, but most chillers require a.c. and, therefore, an inverter of some sort.

The optimum size of components of a photovoltaic system can be determined from Fig. 1. This Figure was prepared using hourly calculations of the output of a fully tracking collector located in Albuquerque, New Mexico, and in Omaha, Nebraska. The weather data were measured in 1962. (A fully tracking system was chosen to simplify the calculations, but the same kind of analysis could be used for a nontracking system.) The Figure shows the peak capacity of the array and the number of days of storage required to achieve different levels of reliability in a system designed to meet a continuous 1 kW load. The load can be met 100% of the time with a large array and a relatively small battery system (a system which would be chosen if cells were relatively inexpensive and it was preferable to waste cell output rather than purchase more batteries), or a large battery system and a relative small array whose average output only slightly exceeds the average annual

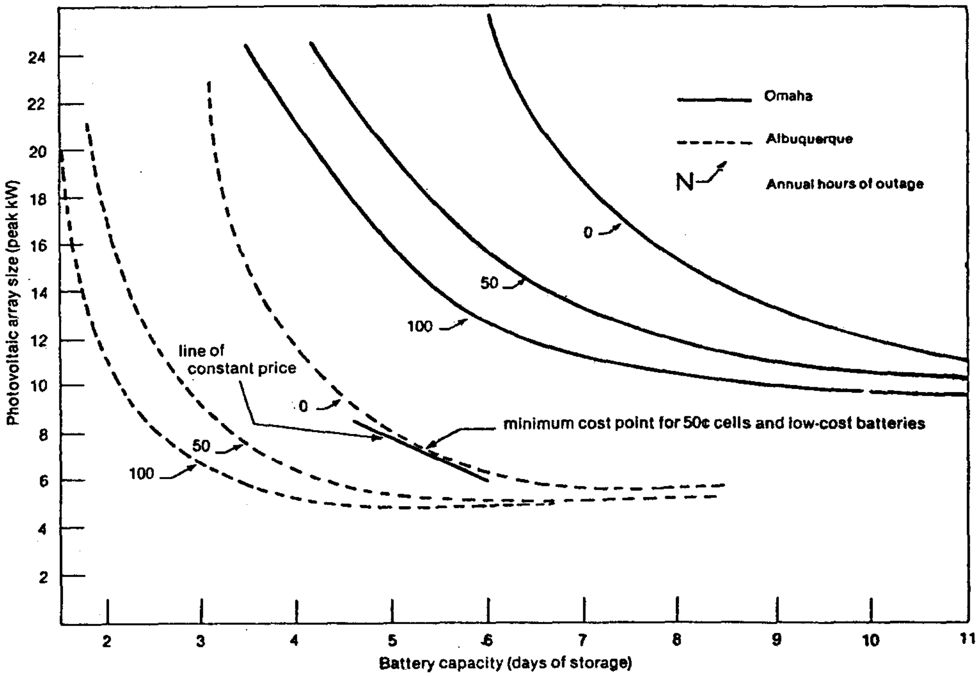

Fig. 1. Photovoltaic system performance (one continuous kW).

demand. Since most of the components of the photovoltaic system are modular, the price of a combined array and storage system can be approximated by a linear function of the array size and storage capacity. Contours of constant price can, therefore, be drawn as straight lines on Fig. 1. The lowest cost system can be determined by the lowest price line tangent to the curve representing the desired reliability.

The slope of the price lines, and therefore the optimum sizing chosen for the system, will depend on the relative price of the array and storage components, and the required rate of return of the system owner.

This analysis will assume that the potential customer compares options using a "life-cycle" costing analysis based on maximizing net returns on investments. Some customers, of course, will choose systems entirely on the basis of first cost — the equivalent of an infinite required rate of return — but this simplification may become a luxury in an era of rapidly rising fuel prices. In the example reviewed here, it will be assumed that the owner expects a 15% return on all investments. Using such an analysis, the average annual cost for a device with a ten-year life is approximately 0.20 × (the initial cost of the device), and the average annual charge for a device with a 20-year expected life is 0.16 × (the initial cost). These are simply the capital recovery factors for a 15% interest rate during a period equal to the system's life.

These multipliers can then be used to compute constant price lines:

$$\text{(price)} = 1.3 \times [(0.16) \times \text{(installed array cost)} + (0.20) \times \text{(installed cost of battery)}]$$

The factor of 1.3 has been included to cover contractor markups, contingencies, and other indirect costs. No added charge has been included for maintenance since it is assumed that maintenance can be performed by crews servicing the communications equipment.

Table 1 indicates the intersection points for several possible current and future systems. Intersections are computed for three different array costs; $10 per peak watt (near-term prices), and the 50c and 20c price goals. It is assumed that mounting and installation costs are about $2.50 per peak watt and that this price can be reduced to 60c per peak watt by increasing the packing factor of the cells (and perhaps increasing cell efficiency) when lower cell costs are achieved. Two battery prices are assumed; (1) a battery system costing $88 per kW h (including a building to house the system); and (2) a battery system costing $19 per kW h. The batteries are assumed to last 10 years, the arrays 20 years.

Costs of conventional energy systems are summarized in Table 2. Capital costs can be computed as shown above. The effective annual cost of fuel and operating expenses (C_{av}) can be computed from the initial annual

TABLE 1

The cost of energy from a photovoltaic system designed to provide one continuous kilowatt of electrical power*

	Optimum array size (peak kW)	Optimum battery capacity (days)	Effective cost of electricity ($/kW h)
Near-term system costs	5.5 (11.5)	6.25 (10.25)	1.85 (3.73)
Current cell costs, low cost battery	5.0 (10.5)	7.0 (11.5)	1.48 (3.09)
50c cell and current batteries	13 (23)	3.75 (6.5)	0.52 (0.92)
50c cell and low cost battery	6.5 (13)	5.5 (9.0)	0.23 (0.44)
20c cell and low cost battery	9.0 (15)	4.5 (8.0)	0.23 (0.38)

*The first number of each pair refers to a system located in Albuquerque, N.M., and the second number, in parentheses, refers to a system in Omaha.

Notes: It is assumed that the batteries are 75% efficient and power conditioners are 95% efficient in charging and discharging storage. Wiring and power conditioning costs associated with expensive arrays are assumed to cost $200 per peak kW; these costs are assumed to be $100 per peak kW for the inexpensive arrays. The other capital costs assumed are indicated in the text.

TABLE 2

The cost of energy for a remote communications facility served by a diesel powered onsite generating system

Item	20 kW system			2 kW system		
	Cost ($)	Life (yrs)	Levelized annual cost ($/kW)	Cost (1978)	Life (yrs)	Levelized annual cost ($/kW)
1. Building, fuel storage	80 000	20	640	35 000	20	2 800
2. Engines, controls, etc.	30 000	10	300	5 000	10	500
3. Batteries (12 h) & power conditioning	17 000	10	170	1 700	10	170
4. Maintenance	20 000 (per yr)	20	1 600	5 000 (per yr)	20	4 100
5. Fuel	24 700 (per yr)	20	1 230	2 470 (per yr)	20	1 230
6. Total	–	–	3 940	–	–	8 800
7. Effective cost of electricity ($/kW h)	–	–	0.45	–	–	1.00

Notes: Cost of components based on review of material generated by the BDM Corporation, Aerospace Corporation, Intertechnology Corporation and Gnostic Concepts, Inc. Fuel is assumed to cost 60c/gal. in 1978 and fuel prices increase at 2% above inflation. The efficiency of the engine–generator–battery charging system is assumed to be 20%.

cost of the service (C_o), and the rate at which the cost is expected to increase with time (*e.g.*, with inflation) as follows:

$$C_{av} = C_o \frac{\sum_{t=1}^{T} \left(\frac{1+i}{1+r}\right)^t}{\sum_{t=1}^{T} (1+r)^{-t}}$$

where i is the annual rate of increase, r is the expected rate of return, and T is the system life. In the analysis which follows it will be assumed that operating expenses increase with inflation (assumed to be 6%) and that conventional energy prices increase 2% faster than inflation. Using this assumption and a 15% rate of return C_{av}/C_o is 1.64 for operating expenses and 1.90 for conventional energy.

It can be seen that there are large economies of scale for remote onsite power facilities, at least up to the 20 kW system. Making a crude interpolation of the data, it seems that if battery prices are not reduced, cell costs must fall to 3 - 4 $/peak watt to compete with the 2 kW system in an Albuquerque climate and to 0.50 c/watt to compete in an Omaha climate. (Many repeaters are located on mountain peaks or other areas with relatively clear weather and the Albuquerque climate would be the more representative.) If battery prices can be reduced significantly, systems at 5 - 6 $/watt would be competitive in the Albuquerque climate. Competition is significantly more difficult in the case of the larger system. A 50c cell is required in an Albuquerque climate and competition in an Omaha climate will require both 50c cells and an inexpensive storage.

It is important to recognize that the high cost of the photovoltaic systems used in these installations is due to the fact that they are designed for 100% reliability. Much lower costs are possible if some power source is available for short periods. If a photovoltaic system in an Albuquerque climate can fail to meet the load for 50 h per year, a photovoltaic system can be constructed which is capable of providing electricity for $1.62/kW h using equipment available at current prices. This kind of outage may be tolerable in developing nations. Rural telephone systems in Mexico, which provide only about 60 min per day of service, for example, have been very well received [10].

It may be possible to reduce costs for continuous service systems by using a simple gasoline powered emergency generator for short periods. If an emergency backup system is available with an operating cost of θ_e per hour, the cost of a combined photovoltaic, emergency generating system can be minimized in terms of the number of hours of allowed photovoltaic system outage, N, with the following relationship:

$$\partial P(N)/\partial N = \theta_e$$

where $(P(N))$ is the annualized cost of the photovoltaic system designed to allow no more than N hours of outage.

Some savings can also be realized if the system need only operate during the day. Figure 2 compares the zero-hour outage curves for systems designed to provide a continuous one kilowatt design with curves for systems designed to provide 3 kW for the period from 8 a.m. to 4 p.m. and zero power otherwise. It is apparent that the daylight load reduces costs significantly in an Omaha climate but has little effect in an Albuquerque climate.

One problem with the kind of analysis described here, of course, is that it requires statistical information about the sunlight available at the communications site. Such information is rarely available for remote areas. In some circumstances, however, the savings realized if such data can be obtained could justify work to monitor the solar resource at the site with onsite recording equipment or an analysis of weather data from satellites.

It must be recognized, however, that there are barriers to photovoltaic systems other than economics. Investors are understandably reluctant to invest in new concepts, particularly when adequate actuarial data may not be available on system performance. Potential investors overseas may be reluctant to use photovoltaic systems which require imports. This problem may be counteracted to some extent by the fact that international lending institutions and national economic assistance programs may be interested in subsidizing the installation of photovoltaic equipment. Solar-based equipment does not commit the recipient nation (or the granting organization) to the maintenance of fuel supplies.

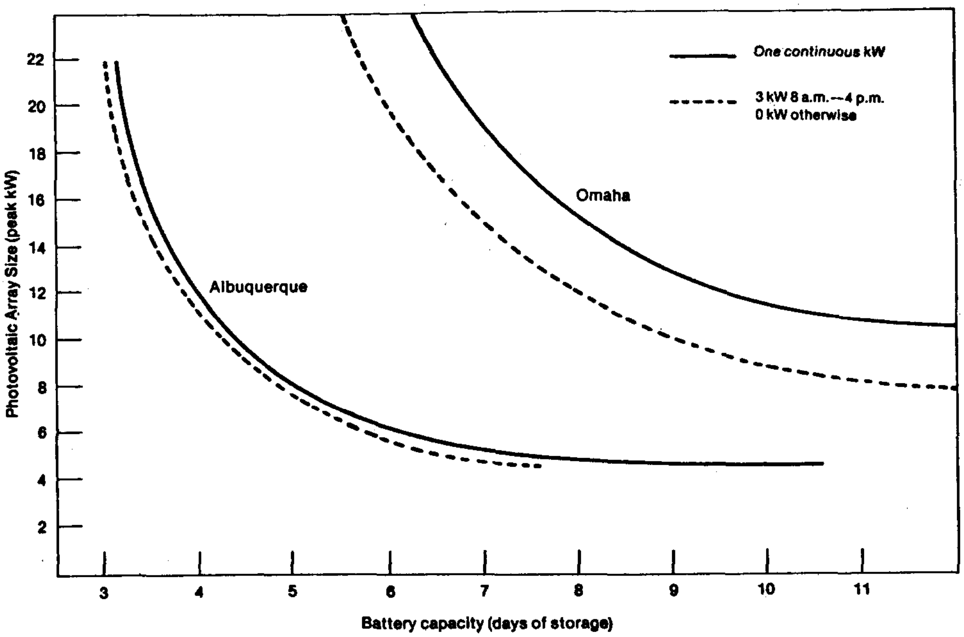

Fig. 2. Photovoltaic systems performance (0 hours annual outage).

U.S. sales in international markets may be limited by foreign competition. A number of nations are beginning to compete for the international photovoltaic market in communications: La Radio Technique — Complec, a French-based subsidiary of the Philips Corporation; A.E.G. Telefunken in Germany; and the Sharp Corporation in Japan are all actively cultivating the photovoltaic communications market [11]. The Indians and Mexicans are seriously considering the development of their own photovoltaic manufacturing facilities.

Conclusions

It can be seen that photovoltaic systems which may be available during the next few years may be able to compete with conventionally powered communications systems. Some photovoltaic systems are clearly attractive at today's prices, although most current applications will be found in systems smaller than 2 kW or in areas where the cost of conventional systems is unusually high. The applications possible in the next few years may, however, make it possible to introduce some kind of communication equipment in areas where such equipment would otherwise be difficult or impossible to operate. If the goals of the Department of Energy's photovoltaic and energy storage programs are met, the equipment may well be economically attractive in many major communications installations in the U.S. where conventional energy could only be produced with a dedicated transmission line costing

$6 - 10 000 per mile. Meeting the price goals, however, will depend to a large extent on the federal support given to photovoltaics during the next few years.

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References

1 Gnostic Concepts, Inc., Photovoltaic power systems market identification and analysis, August 23, 1977.

2 *Ibid.*

3 Statistics prepared by the U.S. Agency for International Development from telegrams sent to AID missions in August, 1977.

4 The BDM Corporation, Characteristics of the present worldwide photovoltaic power systems market, May, 1977. The InterTechnology Corporation, Photovoltaic power systems market identification and analysis, August 23, 1977.

5 Photovoltaic Program, Division of Solar Technology, *U.S. Dept. of Energy (DOE/ET-0019-1),* 1978.

6 These approaches are summarized in H. C. Kelly, Photovoltaic power systems: a tour through the alternatives, *Science,* 199 (1978) 634.

7 R. L. Moon *et al.* (Varian Associates), Multigap solar cell requirements and the performance of AlGaAs and Si cells in concentrated sunlight, presented at the *13th Annu. Photovoltaic Specialists Conf.*, Washington, D.C., June, 1978.

8 G. F. Hein *et al.*, Impact of balance of system (BOS) costs on photovoltaic power systems, (NASA-Lewis).

9 Electric storage systems compatible with photovoltaic apparatus are summarized in Chapter XI of OTA's *Applications of Solar Technology to Today's Energy Needs,* June, 1978. See also Applied research on energy storage and conversion for photovoltaic and wind energy systems, General Electric Space Division, prepared for the National Science Foundation and the U.S. Dept. of Energy, *contract number NSF-75-22221,* January, 1978.

10 E. J. Perez *et al.*, Photovoltaic rural telephone station realized under Mexican technology, *13th Annu. Photovoltaic Specialists Conf.*

11 R. Spongberg, (SERI), personal communication, July, 1978.