Solar Electricity - A Low Power Technology*

L.B. Harris
Department of Applied Physics, University of New South Wales,
Australia

The large size and small power output of solar electric systems are obstacles to high power usage, but realistic low power applications can make a valuable contribution to world energy needs.

INTRODUCTION

Almost the sole object of current research on solar cells is a reduction of their cost, progress being charted by comparison with various projections of when solar electricity will become cheaper than grid electricity (Coutts 1978). Solar cell arrays represent considerable capital investment, and the present cost of solar electricity at about $\$10/W_p$ needs to be reduced by a factor of between 20 and 50, a cost of $\$0.50/W_p$ being considered economic for small photovoltaic arrays while $\$0.20/W_p$ is needed for large-scale use. (Since incident solar radiation varies in both intensity and angle of incidence, the performance of solar cells is measured in terms of peak watts, obtained when strong sunlight, of value 1 kWm^{-2}, is incident normally on the cell.) Target dates for these cost levels to be reached were originally set at 1986 and the year 2000 respectively (Coutts 1978) but the 1986 target has since been revised to $\$2/W_p$

Photovoltaic electric power has received much publicity in the context of the so called energy crisis, which focuses on the need to find alternative energy sources to relieve the drain on our finite supply of fossil fuel, and it is implied that the advent of the cheap solar cell will be able to solve at least some of the world's major energy problems. It is instructive, therefore, to turn to actual solar electricity use, which is helping to solve minor energy problems of relatively small groups of people.

Solar electricity has two uses: in space vehicles and satellites, where high cost takes second place to the need for reliable service, and in remote regions on earth for low power purposes, such as communication systems and navigational aids, where a compact solar design is found to be economical. Increased use might be expected to develop from more diverse applications of small photovoltaic arrays, the size of the array increasing as the cost of solar cells decreases. Predictions are for extension first to household use at remote farms, then to rural electrification networks and finally to large-scale systems adjunct to the main grid, such a progression keeping step with the rising cost of fuel for the diesel generator that is the present source of electricity for remote households. The practicalities and economics of solar electricity are assumed to be controlled by solar cell cost. Is this, in fact, the prime factor limiting practical operation?

Limitations apart from cost are to be found in the need for storage and in the low power

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capacity of systems. Storage is necessary because sunlight is received erratically on earth during the day and not at all during the night, and because most applications of electricity need a supply that is both stable and continuous. The solar cell has the advantage of converting radiation directly into electricity and this advantage would be lost if a non-electric form of storage were adopted. Fortunately an electric form is available in the storage battery, which receives and delivers electricity directly, and since the storage battery and solar cell are both low voltage, modular, DC devices they can each be built up into units of appropriate size that match each other in performance. This compatibility has contributed greatly to the development of small photovoltaic systems. Other forms of storage have been conceived (Pulfrey 1978, McGeehin 1980), such as flywheels, pumped water storage when development has progressed to large central photovoltaic power stations and electrolysis of water leading to hydrogen storage in some future hydrogen economy (Williams 1980), but for all practical purposes there is no immediate alternative to the storage battery.

The elements of a small system are shown in Fig. 1. Solar cells are available in modules containing some 35 individual cells in series, giving an output voltage that might, for example, charge a 12 V battery at a current of up to 2 A. Modules are made up into arrays. For example, an array of four parallel branches each of three modules could supply charge to a 48 V battery bank at currents up to 8 A, giving an output of some 360 W in bright sunlight. The power density (W m^{-2}) of solar arrays is low. This comes about firstly because solar intensity is low (about 1 kWm^{-2} for bright sunlight) and secondly because the conversion efficiency of solar cells (theoretical maximum just above 20%) is also low. Hence, peak power density cannot greatly exceed 200 Wm^{-2}. In practice, the inactive packing around each cell and a lower than theoretical efficiency give a present-day value of about 60 Wm^{-2}. Hence, an area of 6 m^2 provides some 360 W in bright sunlight but the load that can be continuously operated when allowance is made for cloud cover and night time periods is much smaller. The ratio between array peak output and continuous load in telecommunications use under best sunlight conditions is 6:1. Hence, power density referred to a reliably serviced load will be no greater than 10 Wm^{-2}. It follows that solar electricity needs large arrays to power small loads. Fortunately, there are valuable applications where this is no handicap. Scaling up to high-power applications, however, results in a proportionate increase in size that may not always be acceptable, particularly since overall efficiency remains independent of size and gives no economy of scale.

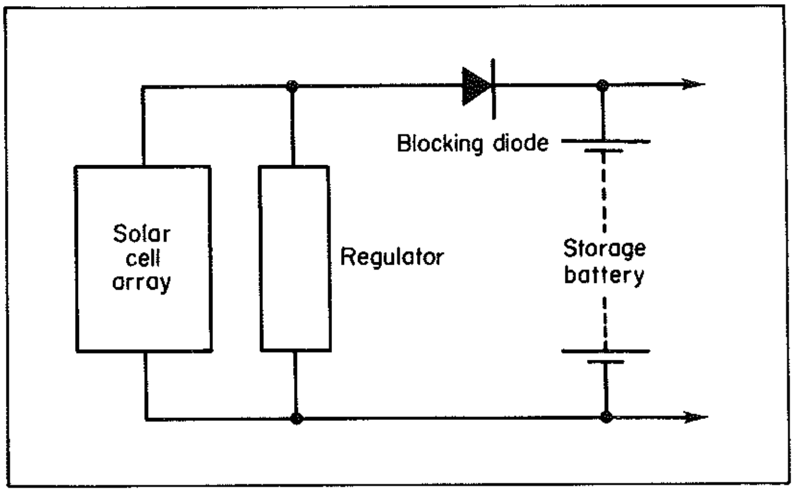
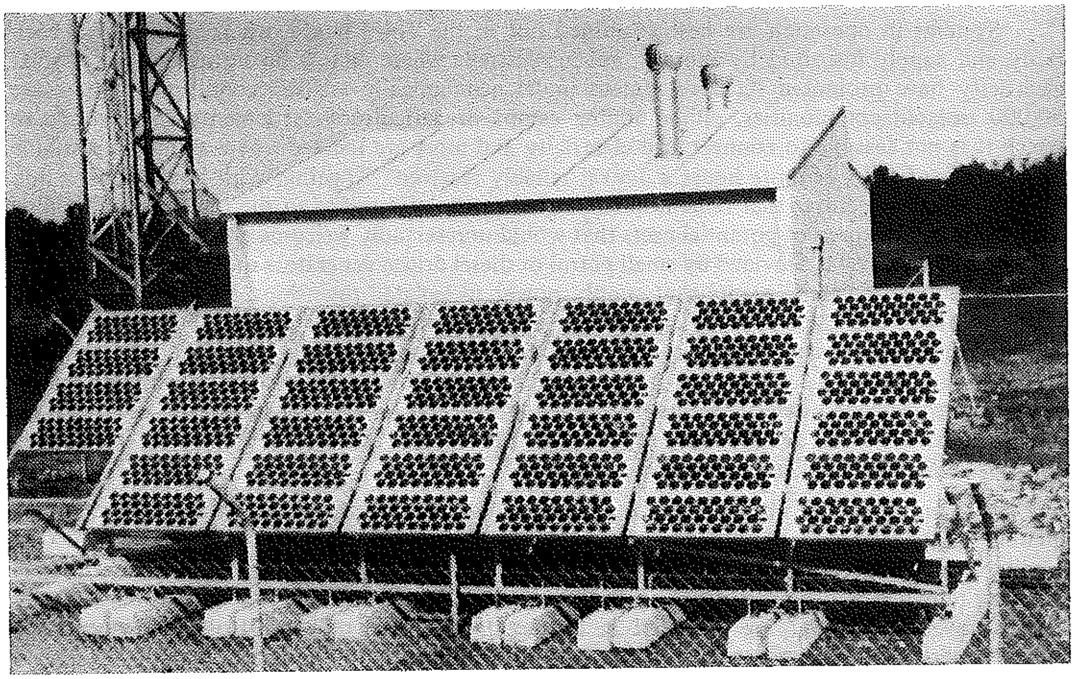


Fig. 1 Simple solar electric system supplying DC. Incorporation of an inverter could give AC.

The compatibility between solar cell and storage battery stems from the fact that both are low-performance devices. Many readers will no doubt be well aware that the reason we do not see large numbers of electric cars on our roads is that present-day secondary batteries have inadequate performance (McGeehin 1980, Hooper and McGeehin 1981). The two types in general use, lead-acid and nickel-cadmium, have broadly similar characteristics. The former is a cheap and efficient unit for starting a car, the latter a compact device for starting diesel engines, and both can provide standby or emergency power but neither is acceptable, on either economic or technological grounds, for storing large quantities of reusable energy. The nickel-cadmium battery is more reliable and more rugged, but for solar electric use it can be up to four times more expensive, and hence the lead-acid battery is the one usually found in service.

The energy density of both batteries is low, which means that the amount of electric charge stored in a given weight or volume of battery is relatively small. Actual values are close to 30 Wh kg^{-1} and 60 W h dm^{-3} and to illustrate what these figures mean, consider a conventional house in a sunny location powered entirely by solar electricity, where it is (optimistically) estimated that the maximum period the sun will not shine is four days. A conservative figure for power use per day is 10 kWh, so a storage battery of 40 kWh is needed. Such a battery will weigh 2 t and occupy 6 m^2 of floor space. A solar array providing some 5 kW_p would be needed, covering an area of 80 m^2. Such forbidding magnitudes are inherent in the operation of low power devices. The diesel generator which is to be replaced operates on fuel with a high energy density (10 kWh per cubic decimetre or per kilogram though perhaps only a quarter of this appears as electrical energy), provides high power and is more economical in a large size. It is thus clear that limitations of size and of low capacity, as well as those of cost, mitigate against the extensive spread of solar electricity.



One of 23 solar installations by Lucas Industries Australia providing power for communications along the Tarcoola–Alice Springs railway in central Australia. The 40 solar cell modules in front provide 1.2 kW_p; batteries in the shed behind provide 2000 A h of storage at 24 V, sufficient for 10 days use.

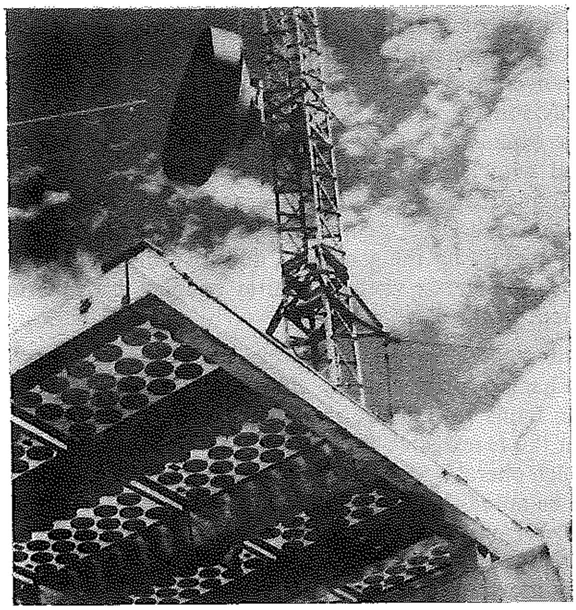
Storage batteries are expensive. The normal car battery has a short life when subjected to the charge-discharge regime of solar duty, as well as a high rate of self-discharge. Storage loss due to self-discharge and to inefficiency in the charge-discharge cycle must be recouped from the solar panel, which must be made correspondingly larger. Batteries with characteristics suitable for solar electricity, including the need for infrequent topping-up, need particular electrode compositions. Materials used include pure lead, low-antimony lead alloy and calcium-lead alloy. A figure of \$250/kWh has been put on lead-calcium batteries, although this would come down with greater volume production. Thus, the battery needed to supply 40 kWh of domestic power referred to above would eventually cost considerably less than \$10,000,but it is necessary to take replacement costs into account since storage battery life is about half the 20 years expected for the solar array (Coutts 1978).

Storage difficulties – the high cost and low capacity of batteries – have been said to rule out widespread use of solar electricity in the UK (Hill 1978), but to leave scope for solar cell use in the high-insolation undeveloped regions of the Third World (Coutts 1978), the argument being that a more reliable supply of sunlight needs less storage and that the urgent needs of the Third World make the practical small system more acceptable. Although problems of cost, size and power level are diminished by transfer to the Third World, they are not eliminated. It is still preferable to store energy from solar cells and windmills in batteries (Logan 1980), and it is still necessary to provide for the longest period the solar array will be without input. It is therefore important to examine the conditions under which small systems can become viable and what is needed to provide local household electricity in remote regions.

OPERATING SYSTEMS IN AUSTRALIA

Systems in operation are best examined not in the Third World, where progress has been tardy and supply distorted by subsidy, but in Australia where factors favouring the use of solar electricity have promoted its development under economically realistic conditions. There are 50,000 isolated communities, either mining camps or agricultural settlements, in Australia to which it is not feasible to connect grid electricity and most are located where abundant sunshine (an average of eight or more hours a day) is reliably received. Together with households within 100 km of major centres that remain unconnected to the grid owing to the high cost of building spur lines, these represent potential users that would unreservedly welcome cheap solar electricity. At present electricity is provided by small petrol or diesel driven generators or, more economically, by central diesel-powered plants that supply power to isolated townships. Solar cells are manufactured locally and there is a sufficiently advanced industrial and technological infrastructure to allow commercial possibilities to be fully exploited. It is not surprising therefore that Australia has, next to the USA, the second largest private sector consumption of photovoltaic devices. These do not provide domestic electricity, however, but low level power in remote areas for communications, switching devices, navigational aids and electric fences. Facts about the solar telecommunications network are instructive.

Telecom Australia has microwave networks (both in operation and planned) containing numbers of repeater stations, each station having a solar array ranging in size from 800 to 1300 W_p feeding loads between 130 and 200 W (Mack 1979). Array size is determined by load, by the level of solar radiation and by the storage capacity considered necessary, the ratio between peak array size and average load varying from 6:1 in regions of high solar radiation to 9:1 elsewhere. For reliable operation in a remote region receiving good sunlight a battery giving 12 to 20 days reserve at the 10 h discharge rate is considered necessary. Such a large battery, of 1500–2000 A h capacity, is housed in the outback at one end of a standard shipping container. This successful programme, initially made possible by the advent of low drain microwave equipment, is being extended and improved, the aim being to reduce cost by incorporation of microelectronic circuitry



Close-up view of one of 13 solar powered repeater stations installed by Telecom Australia along a 580 km route between Tennant Creek and Alice Springs in central Australia. The 814 W_p array charges 1500 A h batteries and provides 132 W for microwave radio equipment.

into microwave equipment of even lower power drain. In this way system size can be decreased. At the present local price of $\$12/W_p$ solar cells represent only 40% of total system costs, so there is considerable incentive to reduce power level and thereby decrease battery capacity and cost. Reducing battery size by using more frequent and deeper cycling has no long-term benefit, since battery life decreases with greater depth of discharge.

The solar array-storage battery system is thus found to be competitive with the diesel generator at lower power levels, but this partly because diesels do not work well at low loads. Diesels operate in the charge-discharge mode for loads from 200 to 1500 W and continuously at higher powers, the cost of delivered electricity decreasing with increasing size of system. It is accepted that the rising cost of fuel oil ought to make the solar electric system competitive at increasingly higher power levels but the magnitude of the gap to be bridged must also be recognised. Existing stand-alone cost-effective photovoltaic systems seldom reach even a few hundred watts, whereas the median size of diesel generator in isolated rural homesteads in the Australian outback, which is the unit to be replaced in the first stage of extension to rural domestic use, is 8 kW. Thus a scale-up of about 40 is required. This is feasible, as demonstrated by the 8 kW_p array in Saudi Arabia, approximately 29 m X 7 m in area used with a 47 kWh (7800 A h) battery for desalination, or more spectacularly by the 160 photovoltaic tracking arrays in the same country using concentrated sunlight to supply 350 kW_p of electricity to a solar electric village at a cost of $\$47/W_p$. There are however many factors to prevent such systems making an appearance down on the farm.

The sheer size of the required static solar array poses problems, since it must be protected from damage by wind and also kept free from dust. Some reduction in system size is made possible by use of concentrator lenses that raise the intensity of the collected radiation. Systems using concentrated sunlight are less simple, however, since they operate from the direct component of sunlight and thus require regular repositioning during use. They also operate at higher temperatures, which tends to degrade solar cell performance. This may be overcome by cooling with a circulating fluid that conveys heat away for use elsewhere, but this adds a complexity not envisaged in the initial concept of simple rural or Third World use and creates a system in which maintenance costs become important. Concentrating photovoltaic systems are available, complete with microprocessor control for tracking the sun. For example, an array of 12 m X 3 m weighing 1.5 t can supply somewhat over 2 kW_p but it is costly as well as sizeable and it needs to operate alongside a large expensive battery. The hassles of maintenance and hazards of corrosion and explosion associated with lead-acid cells are known and tolerated by the rural community, provided they come in small measure. In fact some 30% of isolated households in Australia operate a small battery powered DC system with average power output of 1.5 kW in addition to the AC system powered directly by the generator, and it seems predictable that the end result of cheaper solar cells will be a moderate-sized solar array coupled to the batteries of this DC system, but without relinquishment of the diesel generator.

Replacement of the generator requires a huge battery bank, necessarily of lead-acid cells since extensive research has not produced any alternative (Hooper and McGeehin 1981), and this is out of the question in terms both of size and cost. The only high performance battery likely to emerge commercially in the foreseeable future from the present large research programme is the sodium-sulphur one, which operates at 300°C and is an improbable candidate for domestic or local rural storage. It should be noted that the diesel generator can continue to run on a wide variety of feedstocks even after diesel oil becomes scarce and expensive. Fig. 2 summarises the present situation of solar electricity use. Low power usage ($\leqslant$200 W) can be successfully exploited but there is little sign of any move to larger scale use. Poor battery performance rules out extensive domestic use of solar electricity needing storage. A design has been proposed for a high temperature lithium battery (Liang *et al* 1978) operating with an energy density of 200 W h kg^{-1} and delivering 50 KWh from a volume of only $0.1m^3$. If figures of this magnitude, giving approximately a fortyfold reduction in size compared with lead-acid cells, could be realised at lower temperatures, solar electricity in isolated households could become a real possibility. The present trend in low power usage, however, is towards smaller size and lower cost, not to the larger powers predicted by those who see the solar cell as a competitor for diesel oil.

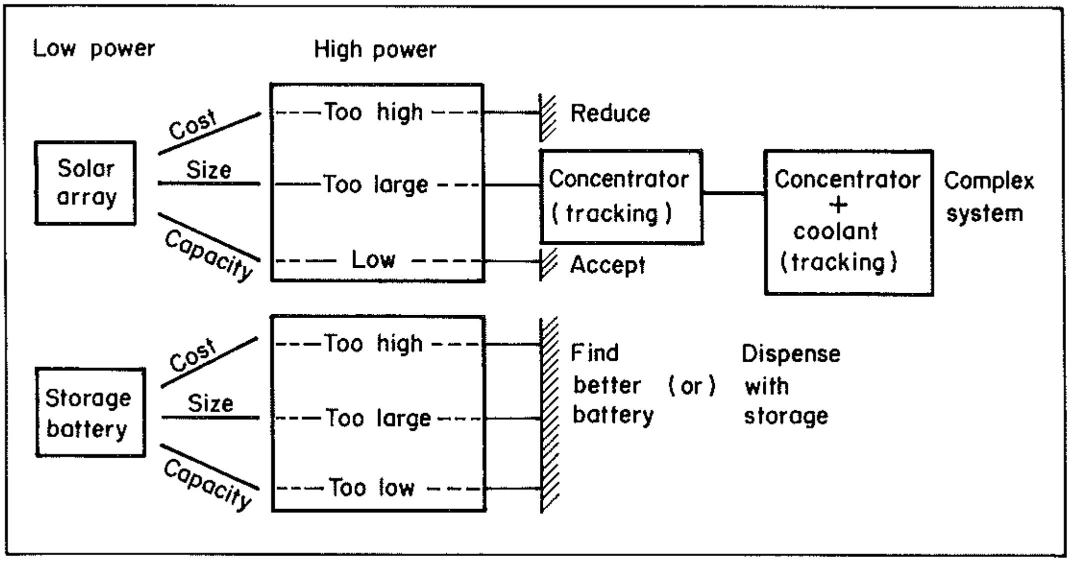


Fig. 2 Factors limiting scale-up of solar electric systems. Where possible, a fortyfold improvement in factors would be desirable.

USE WITHOUT STORAGE

The limitations imposed by the high cost, low energy density storage battery depicted in Fig. 2 are avoided if solar electricity is required only when the sun shines, though it remains necessary to match the application to the lower performance of the solar cell. The solar irrigation pump is advocated for food production on small farms in the Third World since the required peak pumping power of 100 to 300 W per hectare (for farms of 1 or 2 hectares) needs only a moderate sized solar array. Prototype solar pumps, which have peak efficiencies of around 2%, have been found to be several times too expensive. The World Bank has set a ceiling of $\$0.06/m^3$ of irrigation water, a target photovoltaic systems do not reach. Thus though storage is not a problem, since the only item that need be stored is water which is readily retained in small tanks or dams, and though the cost barrier is a good deal less than for household solar electricity, solar pumps are unlikely to go into general use without strong government promotion and substantial subsidy. User governments are, however, wary of transferring a dependence on imported oil to a dependence on imported technology or materials, in this case device-grade silicon. This wariness extends to all manner of small solar cell devices that are claimed to be beneficial.

In Australia irrigation is already efficiently provided by the hundreds of windmills that dot the landscape. Modest power requirements make it possible to replace windmills by solar panels but the benefits of replacing windpower by sunlight are obscure, since the motive power in both cases is free and neither use needs battery storage, and since windmill efficiency, as for example in designs incorporating vertical axis turbines and helical rotor pumping, continues to improve. Solar cells can take over from the windmill industry when substantial savings are seen to accrue, which is possible when markets for solar cells have developed sufficiently for low cost volume production to be a reality. Such markets are not yet in sight. Meanwhile, the windmills keep on turning.

Storage can be avoided by putting solar cells on household roofs and connecting the household solar generator to the grid so that back-up power is available when the sun is not shining. Solar cells on roofs is a concept that captures the popular imagination, even though a modern household not connected to the grid would need, in a sunny location such as the south of France, a large roof-full contributing 5 kW_p, together with battery storage of 150 kWh. Connection to the grid eliminates the battery and allows array size to be reduced and is made feasible by use of an inverter, which provides AC from the solar array to match the supply from the grid. Electricity at low cost from the sun benefits the householder but is of little value to the supplier of grid electricity unless it is used at periods of peak demand so that peak generating capacity within the grid can be reduced (McGeehin 1980). For the most part, peak solar input is out of phase with the peak electricity demand, the latter being usually greatest in winter just after dark. There are exceptions, such as the air conditioning load in phase with the sun in south-west USA. Experimental studies further show that although the installation of a solar array reduces the overall demand for grid electricity, a greater proportion of this smaller demand is required at peak periods. Thus even if cheap solar cells on household roofs were to become practicable, it is not certain that connection to the grid would be an acceptable practice.

It makes sense to keep solar cells separate from the grid. Stand-alone photovoltaic systems have the great advantage of being local – sited at the point of use – which eliminates all transmission and distribution costs. They have the disadvantage of needing a large storage battery. Connection to the grid loses both advantage and disadvantage. It would be preferable merely to eliminate the disadvantage and develop a battery designed specifically for storing household solar electricity. In practice, the types of advanced battery being developed (Hooper and McGeehin 1981), such as sodium-sulphur, are high technology, high temperature ones that need professional attendance and whose eventual use will be the cost reduction of conventional grid electricity. Savings will come from improved load levelling and reduced transmission costs by the siting of storage battery banks near where peak demand is known to be required. This will further limit the need for solar electricity and constrain solar cells to their more appropriate functions of low power operation in remote regions and to non-essential uses without storage, such as 'bonus' air conditioning in company offices. It should be noted, however, that a conjunction of circumstances in the USA has promoted the concept of the 'utility interactive' array which is an array connected to the grid that receives and delivers electricity according to solar input. Further development of this concept depends on environmental, sociological and legal issues that go beyond a discussion on technology.

CONCLUSION

Practical use of solar electricity has emerged as a spin-off from the development of device-grade silicon for the transistor and microcircuit industry. Microelectronics has made great strides by directing high technology towards the use of ever smaller and more complex devices that use lower power and less high cost material. Hence, electronic equipment has not only been able to perform better but also to become smaller and cheaper. Solar electricity that is asked to go in the opposite direction, towards higher power using a conversion technique that shows no economy of scale, finds many obstacles in its path. It makes immediate sense to design down to the low performance capabilities of the solar cell and there are savings to be had by the replacement of primary batteries by solar cells, such as in the solar charger and secondary battery used for signal equipment by the army in the field. Even here, the solar cell faces competition because of its low capacity. As a power source for electronic watches, for example, a solar cell and secondary battery will last longer than a silver oxide primary cell, but with the advent of the high energy lithium primary cell, which can power a wristwatch for up to seven years, most of the advantage of the cumbersome solar cell is lost.

If we persist in wanting high power use of solar cells, the obstacles are fundamental. It is not practical to use solar cells to run a lightweight aeroplane or vehicle that can carry no payload, so we must try to change the cell. But even after high cost single crystal silicon has been replaced by a cheaper alternative, thin film techniques developed for minimal use of active material by continuous industrial processing and conversion efficiency raised to the maximum attainable limit, there will still be need for markets to emerge to allow for low cost, high volume production. There is no way of overcoming the diffuse nature of sunlight, which means that solar arrays must themselves be either diffuse or concentrated into an unreasonably large central unit. In face of these obstacles it seems preferable to restrict the solar cell to appropriate use. Low entropic energy of this kind should not be put to all-purpose use; in particular it is not appropriate that solar electricity should be used for heating, especially since direct use of solar energy as heat is more effective and cheaper. Thus, high power use of solar electricity is not only impracticable but illogical. Let us recognise it for the valuable low power technology it really is.

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