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ABSTRACT

This paper discusses requirements for large earth orbiting power stations that can serve as central utilities for other orbiting spacecraft, or for beaming power to the earth itself. The current state of the art of space solar cells, and a variety of both evolving thin film cells as well as new technologies that may impact the future choice of space solar cells for high power mission applications are addressed.

INTRODUCTION

Starting with Peter Glaser's initial 1968 proposal[1], many people have discussed use of the satellite solar power system [SSPS] as a means of supplying energy to the Earth to replace fossil fuel sources. The recent prominence of the "greenhouse effect" from burning of fossil fuels has again brought alternative energy sources to public attention, and the time is certainly appropriate to reexamine the SSPS.

A recent NASA program, Space Solar Power Exploratory Research and Technology (SERT), investigated the technologies needed to provide cost-competitive ground baseload electrical power from space based solar energy conversion. This goal mandated low cost, light weight gigawatt (GW) space power generation. Investment in solar power generation technologies would also benefit high power military, commercial and science missions. These missions are generally those involving solar electric propulsion, surface power systems to sustain an outpost or a permanent colony on the surface of the moon or mars, space based lasers or radar, or as large earth orbiting power stations which can serve as central utilities for other orbiting spacecraft, or as in the SERT program, potentially beaming power to the earth itself.

A significant risk element for any satellite power system is the photovoltaic array. This was identified twenty years ago in the National Research Council (NRC) review of SSPS[2] as one of the most critical areas where extrapolations from current technology in terms of cost and performance were made. That analysis is still true today.

SPACE AND GROUND SOLAR POWER

A first step toward space solar power will be to demonstrate multi-megawatt power production with ground-based solar arrays. Proponents of SSPS often disparage the

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potential use of ground-based solar energy, possibly considering ground-based systems as a competitor. Nothing could be further from the truth: ground-based and satellite-based solar power are complementary technologies, and satellite-based solar power will only be economically viable if terrestrial power is also viable. This synergy and diversity in space and terrestrial photovoltaics was recently discussed[3] at the 2001 Space Photovoltaic Research and Technology conference.

Experience with ground-based solar power is a necessary step to assess the technology, define and trouble-shoot the manufacturing technologies, and move photovoltaics along the learning curve to low-cost production.

Many ground sites exist in the U.S. with over 300 clear days per year. Flat-plate photovoltaic systems will also provide significant power during overcast days. The difficulty with terrestrial solar power is that it provides power only during the daytime. Ground-based solar power could be viable for a significant fraction of the power needs of the United States due to the fact that the peak loads are typically in the daytime.[4] An additional advantageous feature of terrestrial photovoltaics is the short construction lead-time required and the ability to add capacity in small, modular increments. This allows photovoltaic installations to avoid the uncertainty of forecasting power requirements far in advance, and also allows rapid progress along the learning curve.

In the ten year interval between 1991 and 2001 there was a six-fold increase in worldwide terrestrial total sales and a cost decrease in modules from $6/W to $4/W and a decrease in installed system cost from $12/W to $8/W. There was also a shift, and in some cases a merger, from the four largest suppliers in 1991, ARCO/Siemens, Solarex, Sanyo, and Kyocera, to Sharp, Kyocera, BP Solar, and Siemens/Shell as the four largest suppliers in 2001. Perhaps the most significant statistic in this time period, however, is the shift in use of photovoltaic systems from only 15% grid connection in 1991 to 55% grid connection in 2001. Off-grid use dropped from 60% to 44% in that same time period.

Governments worldwide have encouraged the development of the photovoltaic industry with new manufacturers in India, Korea and many other developing countries. In addition Europe, Japan and the United States are also encouraging both domestic production and domestic markets. Governments have sought to address the relatively high capital start-up costs of the photovoltaic industry by identifying and guiding opportunities between producers and investors, clarifying barriers, instilling confidence in consumers, and improving interactions with other industries that have solved similar problems.

The U. S. Photovoltaic Industry published a Solar Electric Power roadmap in April of 2001.[5] The roadmap goals were to achieve flexible high-speed manufacturing to create a 200 MW factory by 2020. The incremental needs were listed as a 5-fold reduction in module manufacturing costs by 2010, then a 10-fold reduction by 2020 with a 40-fold increase in module manufacturing by 2020. Required actions to achieve these goals were identified as designing of lower-cost module packaging, developing high-volume, high-throughput, high-efficiency cell processes and moving from company-specific equipment manufacturing toward equipment design that can be transferred to and used by more than one manufacturer. Both industry-government and industry-university interactions were seen as critical to reaching these goals. All of these issues are also relevant for future SSPS needs.

Current photovoltaic module production is about 400 $MW_{(peak)}$/year, and increasing by about 40% per year, as seen in Figure 1.

World PV shipments

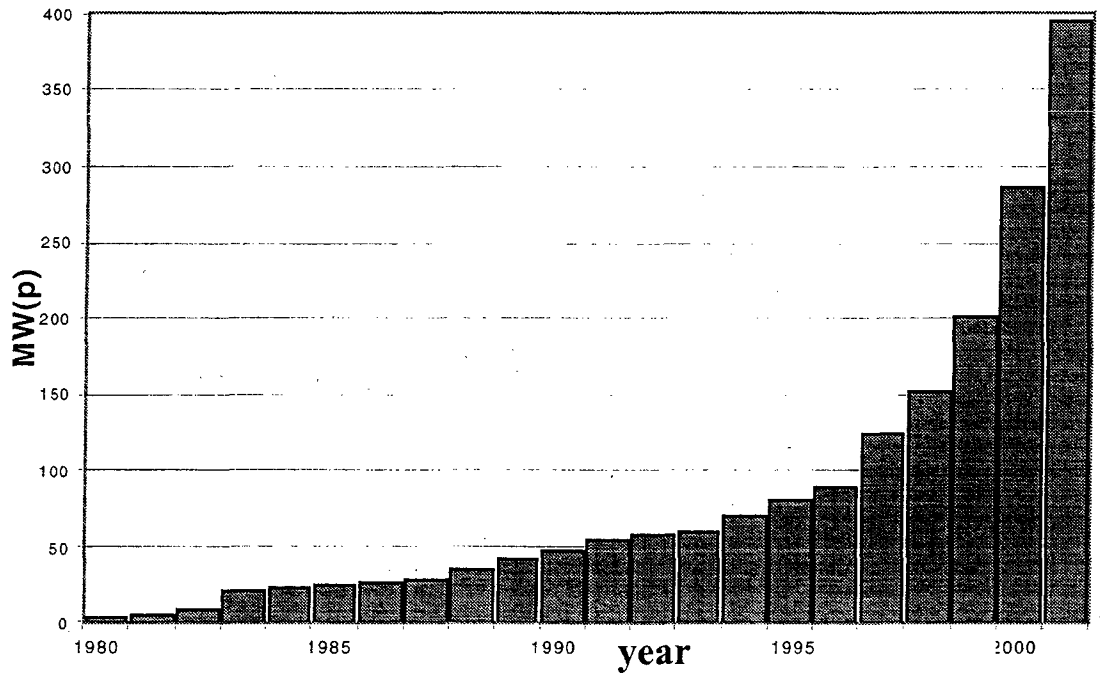

Figure 1: Growth in world photovoltaic array shipments, 1980-2001

Cumulative production of tens to hundreds of Gigawatts will be required for photovoltaics to reach the technological maturity required for finalizing a SPS design.

Having gained valuable photovoltaic experience with solar energy, when the solar generation market share begins to saturate demand for peak power, utilities will begin to search for a solar-energy alternative that provides continuous power.

PV TECHNOLOGIES

As yet it is still too early to chose a technology for SSPS. Among the photovoltaic technologies, many different approaches are still in consideration. One of the leading flat-plate photovoltaic approaches is the use of thin-film photovoltaic materials such as amorphous silicon, cadmium telluride, and copper indium diselenide. Coincidentally, such thin-film materials are inherently radiation tolerant and have the potential for being manufacturable on thin, lightweight substrates. Such materials could be ideal for space use.

Several earlier papers have reviewed the progress of photovoltaic technology.[6,7] NASA recently formed a technology review committee that consulted mission planning offices, solar cell and array manufacturers, and research laboratories to assess solar cell and array technologies required for future NASA Science missions, beyond 2006. The resulting draft evaluation of the state of the art of solar cells and arrays and their potential evolution over the next five years cross-referenced to the mission needs was presented at the 29th IEEE Photovoltaic Specialist Conference in May, 2002.[8] Areas were highlighted where investments in research and technology development are required to meet these mission requirements. There is also an evaluation of the supporting infrastructure required to sustain a

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viable research and technology development program within NASA, while assessing those developments in the commercial sector, which would require very limited NASA involvement. Solar cell and array manufacturers provided both data on current and near term commercial goals and also insight into future development requirements specifically for NASA missions. Program managers provided mission details and the impact on power system needs. There has also been a recent discussion of terrestrial solar cells, past, present, and future.[9]

Current state of the art

Crystalline silicon dominates (~90%) today's terrestrial market. Even though ~100μm of crystalline Si is required for the indirect 90% absorption of light versus ~1μm of GaAs, a direct conversion semiconductor, for the same light absorption, the historical development of silicon technology and high quality material for the electronics industry has insured the dominance of crystalline Si. However, if we look to the future of crystalline Si it is recognized that 50% of the cost of a module is due to the cost of processed silicon wafers. In the past the PV industry has relied on reject material from the semiconductor industry that was available at low cost. This dependence on the semiconductor industry has led to cycles of low supply and high cost material. The feed stock supply of silicon is currently a significant issue. New technologies are hoping to replace the Czochralski grown 100 kg ingots with poly-crystalline, ribbon, or thin-film crystalline production. Each of these techniques has yielded lower efficiencies than crystalline Si. However, over time, the efficiencies have been steadily improving.

Approximately 10% of today's terrestrial market is in thin film materials such as amorphous silicon, crystalline and amorphous heterostructures, copper indium diselenide (CIS), cadmium telluride (CdTe), and dye-sensitized cells. Other types of organic/inorganic solar cells may also be of interest in the future.

Single-crystal solar cells have been used to produce electrical power on almost all space satellites since 1958. Their scalability, reliability, and predictability, have made solar photovoltaics the prime choice for spacecraft designers. Cell efficiencies have grown from 8%, Air Mass Zero (AM0), on Vanguard I, the world's first solar powered satellite, in 1958 to 14.2% efficient crystalline Si cells on the International Space Station (ISS). In the last decade there has been a transition to today's ~27% efficient multi-junction cells, GaInP/GaAs/Ge, that are commercially available from several vendors. It is likely that production efficiencies will exceed 30% in a few years. Higher efficiency cells and arrays are almost always a benefit. Higher efficiency results in smaller arrays that can be used to generate the same amount of power as less efficient arrays, or makes higher power levels feasible for a given configuration. These smaller arrays require less volume when stowed for launch and present less obscuration to sensors. Traded against this benefit are other parameters such as cost, specific power, and special needs such as high temperature, low intensity low temperature (LILT) and radiation resistance, but the trade tends to favor more efficient cells.

Tables 1 and 2 below list the current status of cell efficiencies for AM1.5 and AM0[3]. Notice that the conversion from AM1.5 to AM0 is ~.88 ± .01 for the thin film cells and ~.95 ± .01 for the high efficiency crystalline silicon and III-V triple junction cell.

Cells	Efficiency(%) AM 1.5 global	Efficiency(%) AM 0	Area (cm^2)
c-Si	24.7		4.0
c-Si	22.3	21.1	21.45
Multi-c-Si	19.8		1.09
Multi-c-Si	18.6	17.1*	1.0
c-Si(thin-filmtransfer)	15.3		1.015
c-Si film	16.6	14.8*	.98
GaAs	25.1	22.1*	3.91
GaAs	23.8	20.7	4.0
InP	21.9	19.3*	4.02
GaInP (1.88ev)	14.7	13.5	1.0
GaInP/GaAs/Ge	31.0	29.3	.25
Cu(Ga,In)Se	18.8	16.4*	1.04
CdTe	16.4	14.7*	1.131
a-Si/a-Si/a-SiGe**	13.5	12.0	.27
Photoelectrochemical	10.6	9.8*	.25

*Courtesy of Keith Emery, NREL. The efficiency and Jsc for global reference conditions (25°C, 1000 W/m^2, IEC 60904-3, ASTM E892 global) were taken from the references and translated to AM0 (25°C, 1367 W/ m^2) using the new ASTM E490-2000 reference spectrum. The calculated efficiency assumes that the fill factor does not change for the increased photo-current. Quantum efficiencies corresponding to the table entries were used in the calculations.

** unstabilized

Table 1. AM1.5 and AM1.0 Efficiencies for Small Area Cells

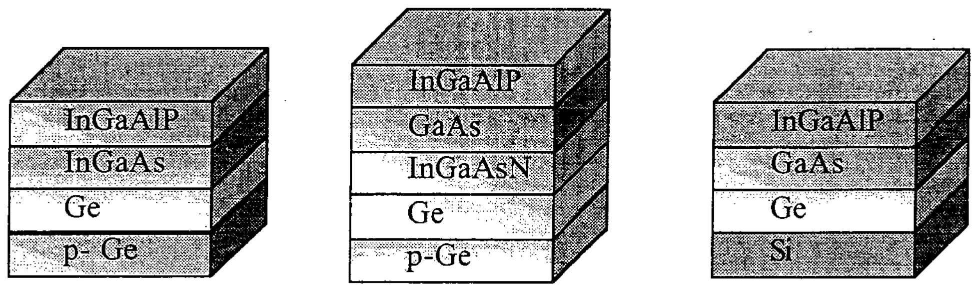
Module	Efficiency (%) Global AM1.5	Area (cm^2)
c-Si	22.7	778
multi-c-Si	15.3	1017
CIGSS	12.1	3651
CdTe	10.7	4874
a-Si/a-Si/a-SiGe	10.4	905
photochemical	4.7	141.4

Table 2. AM1.5 Efficiencies for Modules

FUTURE SOLAR CELL DEVELOPMENT

III-V multi-junction solar cells

Research in the III-V multi-junction solar cells has been focused on fabricating either lattice-mismatched materials with optimum stacking bandgaps or new lattice matched materials with optimum bandgaps. In the near term this will yield a 30% commercially available space cell and in the far term possibly a 40% cell. Cost reduction would be achieved if these cells could be grown on a silicon rather than a germanium substrate since the substrate is ~65% of the cell cost. The advent of a new competitor to the space cell manufacturing market in 1998 and other factors combined to reduce space cells costs by ~ 40% of their 1997 cost in 2002. Several possible cell structures for future III-V devices are illustrated in Figure 2.



Lattice mismatched cell
Efficiency ~30%

Quadjunction cell
Efficiency ~35%

Triple junction on Si
Efficiency ~ 30%

Figure 2. Proposed structures for III-V tandem cell development

The problem areas with projected III-V cell development include the material growth difficulty of the InGaAsN 1.05 eV bandgap material, minimizing defect growth in lattice mismatched material, and current limiting in the Ge subcell. Longer-term projects in the area of multi-junction III-V cells would include the potential of growing these cells on a low cost ceramic substrate and the possibility of efficiency enhancement by nano-structures. With a recurring interest in terrestrial concentrators, both the space and terrestrial communities have common goals for high efficiency III-V cells.

High-temperature cells

In one of the proposed design for a solar power satellite, the "Power Tower" concept, a large-area fresnel lens is used to concentrate sunlight onto a smaller solar array. The proposed fresnel lens has a diameter of ten to fifteen meters, and is proposed to be supported by an inflatable structure. The advantage of this structure is that the photovoltaic array is much more expensive than the fresnel lens material, and hence a low-cost plastic film can substitute for a large area of array.

The difficulty of this approach is that solar cells do not work well at elevated temperatures.[10] Analysis shows that the use of active cooling for the focal plane array is, in general, too expensive to be cost competitive. To make this approach work, therefore, will require development of a new solar cell technology that retains high performance at elevated temperatures. Such photovoltaic technology is being considered for NASA missions such as the Solar Probe.[11] Possible semiconductor technologies that could improve high-temperature performance include GaP, SiC[12], and nitride-based solar cells. While such solar cells have not yet been developed, analysis of high temperature photovoltaic technology is the subject of a research effort at NASA Glenn.

Thin film cells

Thin film cells require substantially less material and have promised the advantage of large area, low cost manufacturing. However, space cell requirements dictate a more complicated trade space. Until recently the focus in space cells has been on efficiency rather than cost. In a several billion-dollar spacecraft the cell cost is relatively small at even a thousand dollars per watt, which is approximately the current array cost. This has primarily been true for spacecraft with power needs from a few hundred watts to tens of kilowatts. However, deployment of a large earth orbiting space power system will require major advances in the photovoltaic array weight, stability in the space environment, efficiency, and ultimately the cost of production and deployment of such arrays.

The development of large space power systems, and a host of other proposed space missions, will require the development of viable thin film arrays. The specific power required is almost 40 times what is presently available in commercial arrays. While high efficiency ultra lightweight arrays are not likely to become commercially available anytime soon, advances in thin film photovoltaics may still impact other space technologies (i.e., thin film integrated power supplies[13]) and thus support a broad range of missions in the next decades. Mission examples include micro-air vehicles, dirigibles, ultra-long duration balloons (e.g. Olympus), deep space solar electric propulsion (SEP) "Tug" Array, Mars SEP Array, and Mars surface power outpost. Spacecraft systems studies which consider the system level implications of increased array area indicate that thin film cells of less than 15 to 20 % efficient would not be cost effective except for certain applications which might involve a high radiation environment, or a stowage volume problem in the launch configuration, or perhaps a unique spacecraft configuration. Current terrestrial thin film programs will benefit the space community as manufacturing techniques are improved bringing the small area cell efficiencies in Table 1 closer to the large area modules in Table 2. The Space community requires that thin film cells must be produced on a lightweight substrate due to the mass penalties imposed in launching. The best thin film cells to date have required processing temperatures in excess of 600°C, which prohibit the use of current polyimide substrates. Research has focused both on finding high temperature tolerant substrates and on reducing the processing temperature of the thin film cell itself while maintaining the higher efficiencies. A low cost flexible substrate would also benefit the terrestrial community by replacing the expensive and fragile heavy glass structures.

Clearly, the ability to increase thin film cell efficiencies would impact both the terrestrial and space cell communities. Semiconductor quantum dots are currently a subject of great interest by both communities. This is mainly due to their size-dependent electronic structures, in particular the increased band gap and therefore tunable opto-electronic properties. A quantum dot is a granule of a semiconductor material whose size is on the nanometer scale. These nano-crystallites behave essentially as a 3-dimnesional potential well for electrons (i.e., the quantum mechanical "particle in a box"). To date these nano-particles have been primarily limited to sensors, lasers, LEDs, and other opto-electronic devices. However the unique properties of the size dependent increase in oscillator strength due to the strong confinement exhibited in quantum dots and the blue shift in the band gap energy of quantum dots are properties that can be exploited for developing photovoltaic devices that offer advantages over conventional photovoltaics.[14] The increased oscillator strength of the quantum dots will produce an increase in the number of photons absorbed and consequently, the number of photogenerated carriers. On the other hand, the blue shift in the band gap energy allows for engineering an ensemble of quantum dots in a size range that will capture most of the radiation from the terrestrial and space solar energy spectrum, see Figure 3.

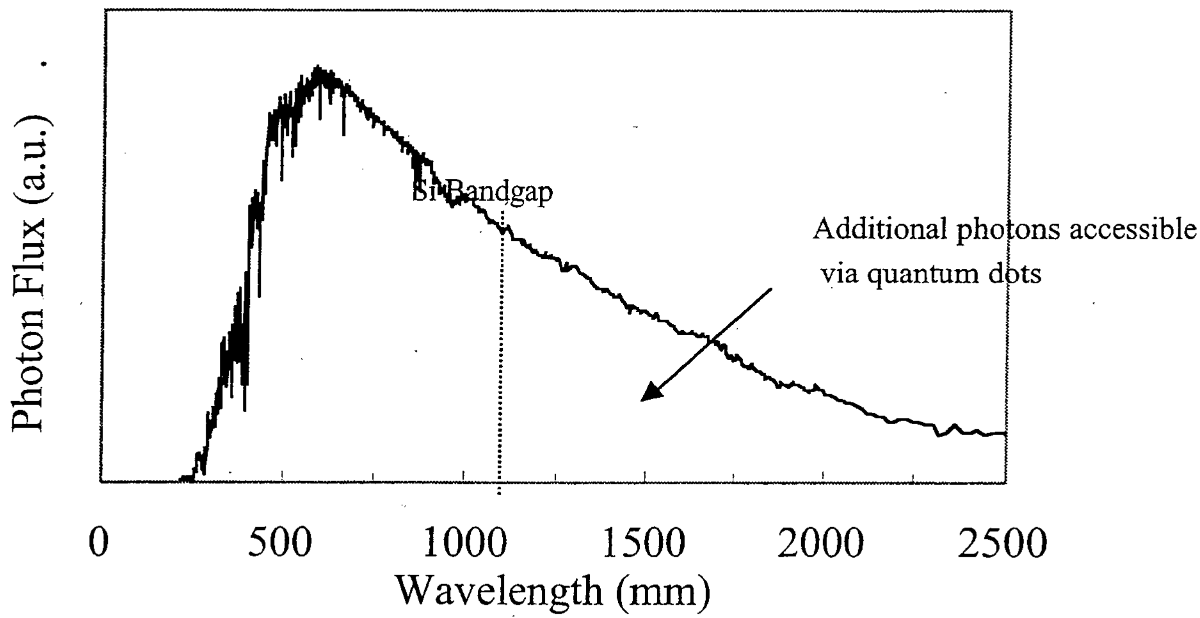


Figure 3. Air Mass Zero Spectrum showing additional photons accessible with a quantum dot cell structure

There have been several proposed methods to improve solar cell efficiency through the introduction of quantum dots. One of the main methods is to produce an ordered array of quantum dots within the intrinsic region of a p-i-n solar cell (see Figure 4).

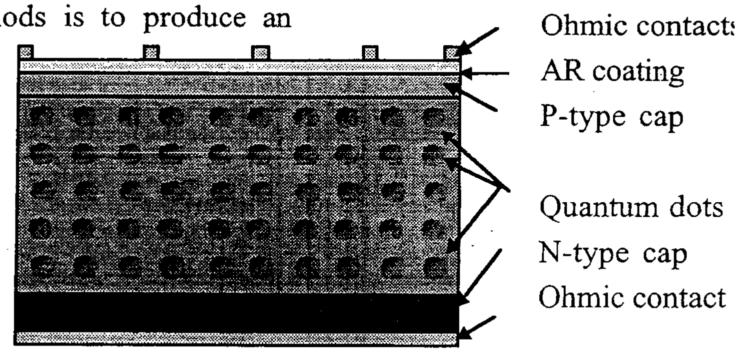


Figure 4. Proposed quantum dot solar cell structure

The overlap of the discrete wavefunctions associated with the electronic states of the individual dots will produce narrow electronic energy bands or "mini-bands." By adjusting the dot size and spacing, a device can be manufactured such that these mini-bands will lie energetically between the valence and conduction bands of the host semiconductor, or, in other words, within their bandgap. The quantum dots in an intermediate bandgap solar cell can be thought of as an array of semiconductors which are individually size-tuned for optimal absorption at a desired region of the solar energy emission spectrum. This is in contrast with a bulk material where photons are absorbed at the band gap and energies above the band gap where the photogeneration of carriers is less efficient. In addition, bulk materials used in solar energy cells suffer from reflective losses at energies about the band gap, whereas for individual quantum dots reflective losses are minimized.

Two additional desirable features of quantum dot solar cell behaviour are the expected superior radiation resistance of such devices and the independence of conversion efficiency with temperature. To a first approximation the energy levels of quantum dot structures are temperature independent. In fact thermal energy assists in populating those levels. This implies a greater thermal stability in contrast to a normal pn-junction solar cell. Unfortunately, it is difficult to estimate the potential temperature range due to the temperature dependence of other cell components.

Both dye-sensitized cells and other organic/inorganic hybrid cells may be of future interest. Both efficiency and stability are issues in both dye-sensitized and polymeric cells. However, research efforts in those areas have been rewarding. A current assessment of space qualification characteristics was presented at a recent meeting.[15] While presenting significant challenges, the small amount of needed material and the ability to produce these cells on a variety of substrates make them attractive for future systems.

CONCLUSIONS

Clearly both research and manufacturing development is required to fulfill the promise of light-weight, low-cost photovoltaic power, whether on the ground or in space. Significant strides have been made in many areas, but many more areas will be addressed in the future. Whether in twenty years, or more, there will be viable choices for generating power and we will need them.

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