Concentrating Optics: From Giant Astronomical Telescopes To LowCost HCPV

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Concentrating Optics: From Giant Astronomical Telescopes To Low-Cost HCPV

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Abstract Triple-junction PV cells used at 1000x concentration are both highly efficient and inexpensive, per watt of electricity produced. A power system based on telescope design principles uses these cells to make utility-scale solar electricity at cost parity with fossil fuel. First, sunlight is concentrated by an array of large square dish reflectors, co-aligned in a mechanically-efficient, open spaceframe structure with built-in elevation tracking axis and drive. Second, the concentrated sunlight at each focus is converted into electricity by many cells packaged in a small receiver, with a ball lens and optical funnels to ensure even distribution between cells. This architecture is optimized for minimum cost in high volume production. The large steel and glass elements and the small integrated receiver and radiator are separately manufactured and shipped for assembly in a facility near the solar plant.

Keywords: utility-scale solar electricity, triple-junction cells, back-silvered glass reflector dish, spaceframe structure
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INTRODUCTION

All the fundamentals are in place for solar electric plants using concentrator photovoltaics to grow to supply a substantial fraction of electricity used by the U.S. and the world:

1) Sunshine is the most abundant source of renewable energy. In the sunniest regions of the world, such as the Southwest deserts of the U.S., each square mile receives in a year as much energy as the annual production of a large (650 MW) electricity generating plant operating 24 hours a day.

2) The most efficient device, bar none, for turning sunlight into electricity, is the triple-junction photovoltaic cell operated in highly concentrated sunlight (HCPV), when conversion efficiency exceeds 40%. High efficiency is doubly valuable because it minimizes land use as well as system cost. HCPV systems have the maximum advantage in regions of the highest solar resource where the light is direct.

3) The same triple-junction cells are also the least expensive of all devices for converting sunlight into electricity. Because they perform very well under very high concentration, a very small and thus inexpensive cell can generate a lot of power. For example, at a projected cost of $5/cm^2, the specific cell cost per watt for operation at 1000x concentration is ~$0.16/watt. This is a small fraction of the total installed cost of $1/watt needed for a utility solar plant to be profitable without subsidy[1].

Despite these fundamental advantages, HCPV plants have yet to capture any significant share of the renewable energy market. Their current rate of installation in large-scale plants is only around 1% that of flat PV panels, and their total power output is only a few parts per million of the total U.S. energy supply. The limiting factor that has held back HCPV is the high cost of everything else in the complete system, apart from the triple-junction cells. Thus today's CPV plants cost more than flat panel PV and CSP (thermal) plants, per unit of power output. In 2010, the cost of installed utility plants using flat panels averaged $4.40/watt[2].

HCPV using triple-junction cells at high concentration could provide the best and fastest path to $1/watt. The challenge is to find a way to keep the cost of making and installing the optomechanical systems to concentrate the sunlight, track the sun, and keep the cells cool within this limit. There is a good prospect that this can be done, given the huge existing manufacturing base for mechanical and glass products.

WHAT'S TO LEARN FROM TELESCOPE DESIGN?

My background is in the design, manufacture, installation, and operation of large astronomical telescopes. What are the parallels to low-cost HCPV systems? Large telescopes gather light over large areas, ~ 50 m^2, with optics mounted on a two-axis

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tracker to follow diurnal motion across the sky. As in a solar farm, the goal for the telescope system is to turn incident photons into electrons with the highest possible efficiency. Located on mountaintops, telescopes are built to survive for decades in harsh weather. Permitting issues are a significant cost factor, as they are for solar plants.

What are the differences? The optical concentration needed for astronomy is enormously greater than for solar energy. In order to form sharp images, a good telescope must be capable of concentrating starlight to an area with dimension set by the wavelength of the starlight being detected. Thus when imaging at 2 micron wavelength, light input over an area of 50 m^2 may be concentrated into an area of 4 x 10^{-12} m^2, a concentration factor of ~10^{13}, *ten trillion*. Much of what is needed to do this, including active compensation of atmospheric blurring, is costly and not necessary to concentate sunlight just 1000x for HCPV, but astronomy can provide a fresh perspective. Many of the underlying engineering basics are shared. Building the world's largest telescopes demands an integrated approach to system design in which optical, mechanical, thermal and electrical aspects are brought into perfect balance in service of the sharpest imaging. HCPV requires an equally demanding balance, but now aimed at focusing and converting sunlight into electrical power at very low cost.

HCPV DESIGN CONSTRAINTS

HCPV could be used to make a significant fraction of all electricity only if the installed cost can be brought down to the $1/watt level needed for profit without subsidy. While this cost is several times lower than today's PV or CPV systems, it should be achievable with HCPV. The HCPV cell manufacturing problem is already largely solved, (because the cells are so small and efficient), and the hardware needed for concentrating light and sun tracking is relatively straightforward and amenable to manufacturing methods already developed and proven at extremely high volume production. Here we consider some key design constraints that must guide our design.

Two-Dimensional Concentration and Two-Axis Tracking

Operation of triple-junction cells at low specific cost requires concentration at around 1000x, which in turn requires focusing in two dimensions. Concentration in one-dimension (as in the classic trough concentration of CSP systems) is limited to a maximum of around 100x by the ½ degree angular size of the sun. If at some future time the cost of highly efficient PV cells were reduced to one tenth that projected now for triple-junction cells, i.e. to $0.50/$cm^2$, then one-axis CPV systems would likely be more efficient and less expensive than plants using full-size silicon PV panels on one axis trackers. Such plants currently have much higher market share than CPV. However, such low cell cost seems now out of reach. Thus to take advantage of the very high efficiency of triple-junction cells at low cost we must use optical systems that focus in two dimensions (point focus), such as lenses or dish reflectors, and track in two axes.

Environmental Considerations

Survival in high wind may be the most critical of all the design constraints. Even in generally low wind areas, such as southern Arizona, winds gusts approaching 36 m/sec are recorded over intervals equal to the desired lifetime of a solar plant. A solar plant comprising many two-axis tracking units and carrying large areas of primary concentrating optics must be built so as to suffer minimal damage in such extremes.

Survival strategies include stowing in a position to minimize pressure, clustering trackers so that they shelter each other, and reducing size and height of units so they lie close to the ground where the wind speed is lowest.

Minimizing environmental impact is another important key constraint. The high efficiency of triple-junction cells together with the high energy-to-power ratio of pointed systems on two-axis trackers, result in HCPV systems having the highest energy yield per unit land area of any solar plant, >600 kW/hectare. Further reduction of environmental impact may be realized by minimizing the disruption of native plans and wildlife during the installation of HCPV farms, and by eliminating any consumption of water for cooling or cleaning. These design constraints are important in order to develop public support and trust. This trust will be needed in the US if large areas of land in the Southwest are to be used for solar electricity production.

Size of the Generation Unit – A Free Parameter

An important degree of freedom we have in designing for HCPV is the size of the basic power generating unit, comprising a concentrator to bring light to a focus, and a receiver at that focus. HCPV systems currently being developed show an enormous variation in the capture area and power. Units operating at the same 1000x concentration may operate with 1 watt of sunlight power focused onto a 1 mm cell, or 1 million watts brought to a 1 square meter array of densely packed triple-junction cells. If the basic power generation units are small, many are packaged into modules to be carried by a single two-axis tracker. If the basic power unit is very large, many two axis trackers in a heliostat field may be used to direct sunlight to a single high-power focus. We are free to choose whatever size of generating unit is needed to minimize the cost per watt of focused sunlight power, provided we can tailor an efficient receiver to match.

Compared to HCPV, CSP plants lack this flexibility. Their thermal engines or turbines generally demand high power inputs. Stirling engines may need ~100 kW of input power brought to a single focus, power tower systems up to 300 MW to take advantage of turbines optimized for fossil fuel plants.

AN ASTRONOMER'S SOLUTION

Just as nature has evolved many radically different photosynthesizing plants, many types of solar solutions will surely survive to fill different niches in providing electricity. Here we map out an architecture developed at the University of Arizona that satisfies the design constraints above and uses a "coniferous forest strategy"—long lasting structures extending over many square miles and harvesting sunlight energy summer and winter, year after year.

Our solution exploits the inherently large difference in size for HCPV between the large light-collecting and tracking elements on the one hand and the inherently small conversion device on the other. The system is designed so that the differently sized components may be separately manufactured by optimized mass production methods and separately shipped to an assembly facility at the site. Such a separation is typical of CSP solar plants. However, because we can use generation units of smaller size and power level compared to CSP, we have been able to develop a quite different optomechanical design of high optical effic-iency and also exceptionally low mass and stability.

The collection area of the basic power generation unit in our architecture is 10 m^2. Two factors favor this size for the lowest cost per unit of delivered concentrated sunlight power. The first is that the 10 m^2 area respects the standard width of float glass manufacture (3.3 m). Reflectors of this size can be efficiently manufactured from back-silvered glass at low cost per unit area (see below). Also, a glass paraboloid of this size can be integrated with a very lightweight steel truss behind to make a composite reflector assembly of high rigidity.

The second factor favoring this size is that an extremely lightweight two axis tracker can be developed to support and track an array of multiple power generation units. Figure 1 is a rendition of a prototype now under construction. A deep spaceframe structure holds the array of reflectors and receivers in accurate co-alignment, and also provides well-spaced, stiff nodes for the elevation bearing. As is well known, a deep spaceframe provides maximum stiffness for a given amount of steel. This becomes important for very high volume production, where the overall cost will be minimized by using low-cost construction materials (like steel and glass) in the most weight-efficient structures.

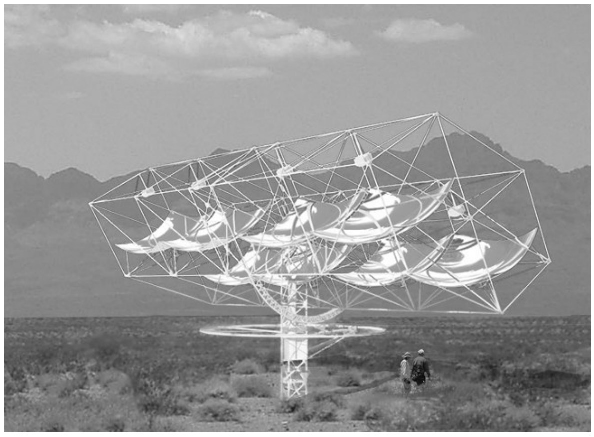

FIGURE 1 Spaceframe tracker with two offset rows of four square dishes, each one 3.1 m x.3.1 m square. The structure is balanced about the elevation axis, which is located at the stiff intersection of three planes running through the spaceframe.

In this design, the pedestal is made high enough so that the spaceframe clears the ground by 2 m. This is done specifically to minimize environmental impact – no blading is required, and native plants and wildlife remain undisturbed. Access roads between alternate rows of trackers require disturbance of only 10% of the land. Despite the extended pedestal height, and the design to survive 36 m/sec wind, use of steel is minimal. The illustrated tracker, which carries 80 m^2 of reflector, requires a total mass of steel of only 2 tons for the entire structure, including the spaceframe, mirror supports, pedestal, and foundations. The total mass of glass carried in the eight reflectors is 800 kg. Given the projected tracker power output of 20 kW, the specific weights for our system are 100 kg of steel and 40 kg of glass per kW of output.

A prototype with a single dish and receiver on a full size tracker has been built and tested in on-sun tests at the University of Arizona, and is described in the accompanying paper in these proceedings[3].

10 m^2 unit reflectors

We prefer reflectors made of glass because of its low cost, high transparency and very high chemical and dimensional stability. These are the same factors that lead to its use and manufacture in enormous volume for windows, for flat PV panels, and for back-silvered reflectors for CSP plants. Reliability has been well proven over 20 years of operation at the SEGS 350 MW trough CSP plant, where 4 mm thick back-silvered glass reflector panels have withstood all but the most extreme hail and wind, with a mean time to failure of 300 years for annealed glass and 10,000 years for tempered glass [4].

At first sight, it might seem that the weight of 4 mm thick glass, 10 kg/m^2, would drive the mass and cost of the supporting tracker. However, the weight of the glass is no more than the maximum operational wind load, and is thus not a major driver of the mechanical design. Cost also is reasonable. Glass reflectors manufactured in very high volume in a dedicated 500 ton/day float-glass plant are projected to cost \$12.50 $/m^2$ or \$0.05/watt. Such a plant will produce annually enough reflectors for 6 GW of HCPV installations.

Dividing the Light

For large power generating units with multiple cells in a receiver, particular attention must be paid to ensure that the high level of sunlight power from the large collector is divided equally among the cells. Such equal division is required for efficient operation of cells connected in a series chain, because the current is limited by that of the weakest cell.

Borrowing from a design long used in astronomical instruments, the receiver in our generating unit places a field lens at the focus, which formats all the incoming light into a sharp-edged image of the reflector dish. The position and distribution of concentrated sunlight is stable against pointing errors of 1/2° off-sun. Equal division of light is made by placing an array of appropriately sized optical funnels across this image. The boundary of the array matches the sharp perimeter of the image, and the gaps between the funnel entrances are minimized, so that virtually all the light focused by the dish is captured. The funnel exits are matched to the light sensitive area of the triple-junction cells immediately behind. This optical strategy is central to the efficient operation of our large power generating units, transforming the “fire hose” of solar power focused by a large reflector to the uniform and evenly divided illumination required by the compact array of cells.

Our strategy of dividing the light uniformly between the cells *after* concentration by a big reflector departs radically from that adopted by the large majority of HCPV systems. In these systems, even cell illumination is ensured by dividing the sunlight into equal amounts *before* concentration. The cells are packaged individually into identical small power generating units, each with its own primary focusing optic and its own heat sink behind, for passive cooling by thermal conduction.

Costs

Can this approach really get to \$1/watt in very high production volume, and will the reliability and O&M costs be low enough for \$0.06/kWh energy cost? Many of the components such as the structure and active cooling system can be manufactured by mass production methods well established by the auto and electronics industries. We are confident that the costs estimated here of the less familiar components, \$0.16 for the cells and \$0.05 for the back-silvered reflectors, are realistic for high volume production. A detailed breakdown of the other costs is given at rehnu.com.

The scale of manufacture needed to move the needle on energy production is the same as that of automobiles. Autos also contain steel and glass, have moving parts and active cooling and electronics systems, and weigh a similar amount. A 20 kW tracking unit weighs 3 tons, the same as an F350 truck costing \$30,000 retail at the dealer’s lot. If the installed 20 kW unit cost were the same, that would be \$1.50/watt. Since the HCPV units are simpler than trucks, they should cost less per kilogram and per watt.

While auto assembly is completed in a factory before shipment, a lightweight spaceframe structure cannot be transported at low cost more than a few miles, must be assembled at a facility local to the solar plant. Structural parts, reflectors and receiver/cooler assemblies will be separately prefabricated, densely packed and shipped to this facility. For large utility plants, the volume will be high enough to justify highly automated assembly like that in an auto factory, so costs can be held to a similar level. For example, a 1 gigawatt plant built over 4 years requires assembly of 12,500 spaceframes each year. Once operation begins, reflector cleaning and maintenance will be on a similarly large scale, with highly automated equipment again used to keep down costs.

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