Concentrating Solar Energy- Technologies and Markets Overview

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Abstract

This paper discusses the concentrating solar technologies used for utility-scale solar power. Specifically, it explains the rationale behind the use of concentration for photovoltaic modules, and how concentrating photovoltaic technologies compare with concentrating solar thermal technologies. It describes innovations in both areas, and how they are addressing the cost challenges to meet the needs of the utility scale market

INTRODUCTION

Photovoltaic modules have been enjoying a surge in popularity recently, as evidenced by the growing number of PV installations worldwide. At 50% average increase per annum over the last 5 years, PV modules have surpassed the 1 GW of production per year. It is interesting to note that when PV modules started in the 70's and early 80's, their cost per watt was astronomical at greater than $20 per Watt. Cost reduction was then envisioned quite differently by two different schools of thought. One school sought cost reduction by reducing the cost of the semiconductor materials itself and the assembly processes of the panel. The other school sought to reduce costs by using less semiconductor material; hence using concentration. Concentrating technologies were used in the 1980's in two different forms. One was by concentrating sunlight on photovoltaic cells (CPV modules), and the other was through the more traditional Concentrating Solar Thermal CST (most times is more commonly referred to as Concentrating Solar Power CSP). The Power Tower CSP technology was demonstrated in Solar One project in Nevada, where mirrors were used to focus the light on a receiver for direct steam generation. The Solar One project was followed by Solar Two project in the early 1990's where molten salt was used as the working fluid with the objective of achieving higher temperatures and enabling thermal storage. The molten salt was then used to convert water into steam whenever electricity was needed- thus enabling electricity to be generated to meet specific load demands and making solar electricity more dispatchable. Another CSP technology using Troughs and synthetic oil as the working fluid found their way to commercial demonstration to the tune of 350 MW installed in the US due to the adaptation of government subsidies, but when the incentives ceased to exist, these CSP companies went out of business.

While concentrating solar technologies struggled to make their way to utility markets because their costs were still too high without subsidies, PV modules found the perfect application where their high prices could be afforded. Distributed solar power, where electricity is generated closer to the point of use, proved that PV panels can be cheaper than extending the grid; hence a market was created. It is interesting to note that early market for PV modules consisted primarily of off-grid applications. This allowed a constant reduction of PV modules over the years with economies of scale and manufacturing efficiency improvements. Later, government incentives and feed-in tariffs pushed demand for PV panels and accelerated the PV installations to the state of where we are today, driving PV consumption to be primarily on-grid in subsidized markets. The emergence of thin film panels, where dramatic material and assembly cost reduction has been achieved, grabbed more market share of the traditional silicon PV panels, and even found some use in utility scale solar power. At issue, however, with thin films is their low efficiency that pushes the total installed cost above $4 per Watt even though the module price itself is under $1.5 per Watt.

Over the last few years, there has been a resurgence of interest in concentrating solar technologies. A few Power Purchasing Agreements (PPA's) that combine to well above several GW have been signed with utility companies for CSP projects. Different technologies within the CSP arena are competing for market share and for dominance in the field. Concentrating photovoltaic (CPV) technology in the mean time has re-invented itself with the utilization of high-efficiency III-V solar cells that were developed for space applications. Several CPV companies now appear ready to commercialize CPV modules side-by-side with CSP systems, with commercial demonstration projects in Spain through the Institute of Concentrating Photovoltaic Systems

(ISFOC). The next few sections describe the landscape of the concentrating solar energy markets and technologies, specifically addressing what has changed to lead to this resurgence of concentrating solar technologies.

SOLAR ENERGY MARKET SEGMENTATION

Figure 1 (taken from Ref. [1]) shows a projected market forecast by 2020 for the different solar energy technologies.

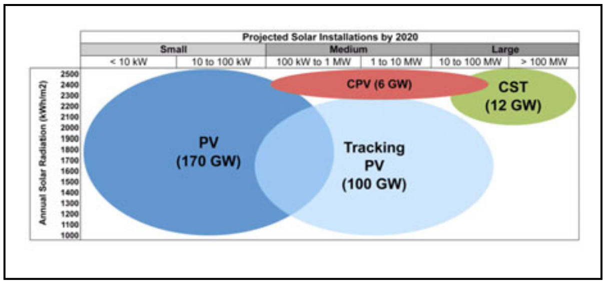

Figure 1- Projected Solar Markets by 2020 from Ref. [1]

While the projected numbers of GW installations in this figure are arguable, what matters here is the distinction of which technology is suitable for which market. The market for flat plate PV panels is indisputable being that of residential and commercial rooftop markets. In this market, electricity is being sold at retail prices and the market is subsidized in different countries, e.g., U.S., Germany, and Spain. Photovoltaic modules and tracking PV modules can also be used for medium size installations. Concentrating solar energies do compete in medium and larger scale utility markets, where electricity is sold at whole prices.

CONCENTRATING PHOTOVOLTAIC (CPV) TECHNOLOGY

The use of III-V semiconductor materials has elevated the level of interest in CPV beyond anyone's imagination. The high efficiency of the multijunction III-V materials, approaching 40% on average under concentrations of a few hundred suns, has revived hopes that CPV systems can actually achieve low cost via increased module efficiency. The efficiency of the multijunction solar cells is quite leveraging in terms of cost reduction, to the point that some CPV systems with 35% multijunction solar cells at $10 per cm^2 will be cheaper than comparable CPV systems with 24% silicon even if the solar cells were provided for free [2]. Further, the multijunction cells are less sensitive to the temperature, unlike silicon cells that have higher temperature coefficients.

There are two main families of CPV systems: those that use reflective optics (such as Solar Systems) and those that use refractive optics (such as Amonix). Reflective optic systems can still be divided into two categories: one that uses dense array of solar cells and one that uses solar cells that are separated from each other. In the case of the dense array systems, exemplified by Solar Systems of Australia, active water cooling is needed. The specific challenges of dense array CPV systems have been discussed in details in [3]. Other CPV systems can in general use passive air cooling.

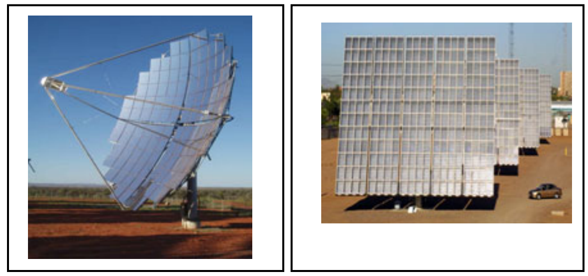

Figure 2- CPV systems that use reflective optics (Solar Systems to the left) and CPV systems that use refractive optics (Amonix system to the right)

The main hurdles towards full commercialization of CPV systems are not insignificant. Most notably, the multijunction solar cells are very complicated and delicate semiconductor devices where latent defects in the material may not be screened before a complete module assembly is put together. And even then, latent defects can emerge a year or two later as repeated exposure to concentration (combination of high current density and temperature) gives rise to defects that could lead to cell degradation or even shunting. Further, packaging of the semiconductor to the substrate for mechanical support and heat extraction plays a key role in the longevity of the semiconductor under concentration. The integrity of the solder joint between the solar cell and the substrate is critical to cell reliability. A fractured solder joint, or one where large solder voids exist will be detrimental to reliability. An excellent reference for the challenges facing CPV solar cells can be found in [2].

Additional challenges exist from the optics side. The concentrated sunlight hitting the solar cells needs to be fairly uniform, not just on the individual cell itself but also from one solar cell to the next. If an array of solar cells is receiving different concentration levels (that can vary by, say + or – 10%), the cell receiving the lowest concentration will limit the current of the entire string. This puts very stringent requirements on the alignment accuracy of the CPV modules. This is especially difficult to accomplish in a dense array structure. The net of all this is that the multijunction solar cell array will perform at lower efficiencies than those that are theoretically possible, or than what individual solar cells will do under concentration.

The state of the CPV technology at this point looks very promising. Many companies have emerged as potential suppliers of the solar cells, unlike the case back in early 2000 when only Spectrolab and Emcore provided commercial concentrating multijunction cells. CPV module makers continue to introduce novel solutions to their CPV modules, and the role that ISFOC has played by giving a platform for the test of early CPV systems cannot be ignored, as it will give investors and customers the confidence they need to proceed with this technology.

CONCENTRATING SOLAR POWER TECHNOLOGIES

There are 4-main CSP technologies: i) Trough technology, ii) Linear Fresnel Reflector (LFR) technology, iii) Dish Stirling Engine technology, and iv) Power Tower technology. We will review these first then discuss some innovations in the Power Tower technology.

Trough CSP Technology

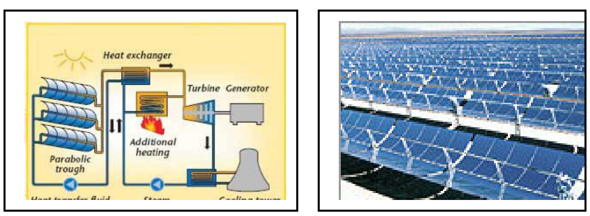

Figure 3- Trough CSP technology

The Trough, shown in Figure 3, is the most mature concentrating solar technology with commercial demonstrations since the 1980's and total installed in the field of more than 350 MW. It utilizes a one-axis tracking system to concentrate the sunlight onto tubes inside which synthetic oil runs and then, through a heat exchanger, converts water into steam that consequently goes through the steam turbine. The concentration level that is achieved by the optics system is low (because it uses single-axis tracking) and hence the maximum temperature achieved is low, driving down the efficiency of the plant and, thus requiring water cooling to increase the plant efficiency. The main advantage of this technology is its maturity. Its main disadvantage, however, is the relatively higher cost and, at times, limited supply of materials. The maturity of this technology leaves little room to bring down its installed cost below the current value of $3.50-$4.00 per Watt.

Linear Fresnel Reflectors

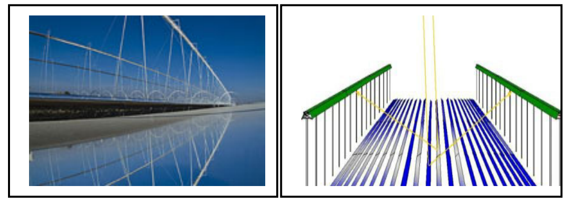

Figure 4- Linear Fresnel Reflectors CSP Technology

Linear Fresnel Reflectors (LFR) CSP Technology

LFR is a modification of the Trough technology. In LFR technology, mirrors track the sun and focus them on a tube where synthetic oil gets heated then goes to heat exchangers to produce steam, or direct steam generation can takes place directly in the tubes. Unlike the Trough technology, the tubes are fixed in place; however, the tracking field is still one-dimensional, the concentration level is low (thus having lower maximum temperature and lower operating efficiency necessitating the use of water cooling).

Dish Stirling Engine

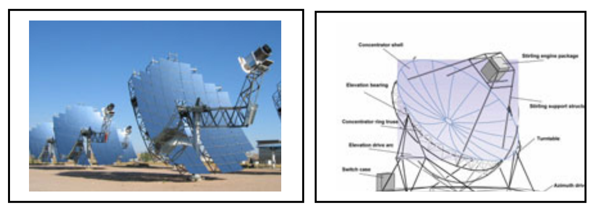

Figure 5- Dish Stirling Engine

The Dish Stirling Engine utilizes a dual-axis tracking system in a tracking dish to focus the sunlight on a Stirling engine. Each dish system produces 10-25 kW and is considered the highest efficiency solar thermal solution available. This technology, however, foregoes some of the most established benefits for concentrating solar thermal in utility-scale applications. Practically, it offers little economies of scale for large-scale projects, making it more suitable for distributed power applications under 10 MW. The use of individual 10-25 kW dish engines for large projects adds significantly to the O&M costs and the requirement on the structure rigidity for wind resistance adds to the project installed cost. Further, Stirling engines are high precision machines that have not been successfully commercialized to date. Finally, the use of the Dish Engine technology offers no advantage when it comes to dispatchability, as it can neither provide storage nor can it be used to hybridize a traditional steam power plant.

Power Tower CSP Technology

Figure 6- Power Tower technology demonstrated by PS-10 project in Spain

The Power Tower technology uses either direct steam generation or molten salt technology. Both approaches have been demonstrated in Solar One in the 1980's and Solar two in the 1990's in California, respectively. The latest demonstration has been in Spain with the PS-10 project, which is shown in Figure 6. The Tower system uses dual-axis tracking mirrors (referred to as heliostats) to concentrate the sunlight on a central receiver that is located on top of a tower. Because of the dual-axis tracking, higher temperatures can be achieved; hence higher efficiency. The molten salt enables storage and therefore even higher plant operating temperature, but it has the disadvantage of requiring the molten salt to be maintained above 120 deg. C overnight to prevent freezing. Tower technology with direct steam generation eliminates the need for costly heat exchangers, and has the potential of being the lowest cost. The PS-10 represents the typical Tower technology, which as can be seen from Figure 6, utilizes large mirrors (each mirror is 120 square meters) that are mounted using poles that are dug into the ground with large motors and drives to rotate the heliostats and get them to track the sun.

Modular, Scalable CSP Power Tower Solution

Until recently, the cost advantage of CSP for utility scale vs. other solar technologies could be materialized only in large scale installations. Recently, eSolar whose headquarters are in Pasadena, California has introduced the concept of modular, scalable CSP solution using the tower technology platform. The eSolar solution is based on small tracking mirrors that are approximately 1/100th the size of the mirrors used for the PS-10 project (see Figure 7a). Their small size enables the use of much less steel, thus greatly reducing the material cost. Further, the frames are mounted on concrete pedestals that do not require digging in the ground, thus reducing the installation costs. The eSolar solution is based on the use of innovative tracking system where camera towers are used to monitor the location of each mirror, and through software controls enable accurate tracking with little human intervention. The eSolar solution is modular, where each module is made up of approximately 12,000 mirrors (divided between a north field and a south field) focusing the sunlight on one receiver for direct steam generation. Each module is capable of generating 2.5 MW electric. Figure 7b shows a picture of the first eSolar power plant in southern California consisting of 2 modules for a total of 5 MW.

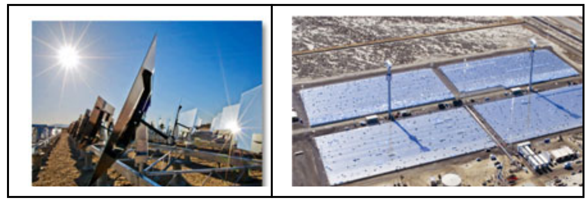

Figure 7- The eSolar modular, scalable CSP solution

CONCLUSIONS

The concept of using concentration to bring the cost of solar electricity down is not a novel concept. What is new here is the innovation that makes concentrating solar technologies economically attractive. In the case of concentrating photovoltaic, the innovation comes primarily from the use of the III-V multijunction solar cells that were originally developed for space applications. In the case of CSP, the innovation is in the tracking system that enables achievement of modular, scalable power plants at lower costs.

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