A 30% efficient (>250 Watt) module using multijunction solar cells and their one-year on-sun field performance

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ABSTRACT

Concentrator systems are emerging as a low-cost, high-volume option for solar-generated electricity due to the very high utilization of the solar cell, leading to a much lower $/Watt cost of a photovoltaic system. Parallel to this is the onset of alternative solar cell technologies, such as the very high efficiency multi-junction solar cells developed at NREL and Spectrolab over the last two decades. The relatively high cost of these types of solar cells has relegated their use to non-terrestrial applications. However, recent advancements in both multi-junction concentrator cell efficiency and their stability under high flux densities has made their large-scale terrestrial deployment significantly more viable.

Amonix has designed, developed and fabricated modules using the high efficiency multi-junction cells from Spectrolab. One of these modules has been deployed at the University of Nevada, Las Vegas. The module has been in continuous operation beginning May 2006. The efficiency has been measured periodically and has shown a range from 26.1 % to 28.5 %. The latest measurement, made on February 20th showed an efficiency of 28.0 % at 956 DNI and an ambient temperature of 13 °C. This excellent stability of the multi-junction module's performance promises to pave the way for future installations of this advanced technology. One short-term example of this is a new Amonix-designed module capable of 30 % efficiency and 300 Watts per module. This module's performance, along with more testing of the long-term performance of the initial design will be presented at the time of the conference.

Keywords: Solar Energy, Multi-Junction, Concentrator, Amonix, History, Peaking Power

INTRODUCTION

Amonix has developed a high concentration photovoltaic (CPV) multi-junction (MJ) module that has been in the field for now over a year. Its first year has shown good stability and efficiency. Another ~1.0 m^2 module has now also been developed that is capable of 30% efficiency and over 300 watts at operating temperature. This CPV module demonstrates the increasing viability of the multi-junction cell for large-scale field deployment and lowest overall cost for solar generated energy.

HISTORICAL DEVELOPMENT

Concentrating PV has had a different road than flat-plate PV and although both journeys have taken longer than expected, concentrator's road has been over even rougher terrain. The idea of CPV has been around almost as long as the thought of commercial flat plate PV, and at its inception was expected to ultimately become the lowest cost technology for solar electricity. This was both through higher efficiency and better material utilization. Research began in the early 1970's accelerating in earnest towards the end of that decade.[1]

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There were several false starts and early attempts, although not unsuccessful, did not fully reach expectations. Three of the larger efforts (Sky Harbor in Phoenix, SOLARES in Saudi Arabia, and Dallas Airport) all had total efficiencies of between 11-13% and only one of them (SOLARES), operated for any extended period of time[1]. This inefficiency understandably, was in large part due to the use of modified one-sun cells in their concentrating systems. Further research saw the eventual emergence of a high-end silicon concentration cell developed initially at Stanford University in California and perfected by Amonix and SunPower. The 'back-junction-point contact" solar cell could withstand some of the high solar fluxes necessary for very high utilization of the solar cell, and promised much higher efficiencies and lower costs. Amonix was one of the pioneers in this technology, bringing to bear its history in space-hardened transistors to make this cell stable under the concentrated sunlight. Currently, Amonix manufactures this cell in a commercial environment and has a world record 27.6% efficiency recorded by Fraunhofer Institute in Germany. This stable high efficiency device was a clear milestone in the commercialization of CPV and projections of costs lower than $2.00/Watt installed were touted.

Again, however, the promise of concentrating PV did not materialize immediately for several reasons. Perhaps primarily, this was due to the lack of necessary funding to properly mature the technology. Flat plate suffered from the same problem, but was different in that it had a market in remote power and space applications, providing it with a small, but important revenue stream. Telecommunication applications in the Australian outback, remote homes in places in the USA, space cells, and roadside call boxes were some of the reasons some flat-plate companies survived.

Another important reason concentrating systems lagged behind flat-plate was the complexity of the balance of plant. Developing a module is one thing, but developing an accurate and reliable tracking concentrating system is a whole other realm. In spite of the daunting challenges facing concentrators, a few companies trekked on. Entech in Texas, Solar Energy system in Australia, and Amonix in California are some of the long standing names that worked diligently to develop systems that were commercially viable.

Parallel to these efforts, several research facilities were working in the development of III-V devices. NREL became the leader and presented a monolithic dual junction cell with over 32% efficiency.[2] Spectrolab and others have since moved the technology forward and today have a triple junction device verified at over 40% efficiency. In another large milestone, this enabling device has pushed concentrating PV back into the full light of the commercial solar energy market.

CURRENT STATUS AND EFFORTS

Since the advent of the latest multi-junction cell, an explosion of effort to try and commercialize this technology has been launched. There have been a number of different approaches from low to high concentration, both refractive and reflective. Perhaps more importantly, the amount of venture capital spent to help this effort has been substantial.

This is really no wonder. The potential of CPV with the advent of the multi-junction cell shows such promise. The ultra-high efficiency of the cell guarantees that the cost of the system external to the cell drops dramatically. The following IV curve shows a ~1.0 m^2 module recently produced by Amonix Inc. that reached nearly 30% efficiency at its operating temperature (see Fig. 1). This is a result of the work that Amonix has done with the financial assistance of NREL as part of the "High Performance Photovoltaic Project" of the DOE, which is to improve module efficiencies up to a level of 33% and higher. Assuming a similar solar cell cost, the installed cost for a concentrating multi-junction cell system compared to the even most efficient silicon solar cell system, could drop by 30+% with this 30% module. The 75 kW field seen below would be transformed into a 105 kW field or higher (see fig. 2). An alternative, though equally valid description is: a $5.00/W installed costs would drop to nearly $3.30/W for the same hardware simply due to the alternate (and more appropriate) rating scheme. Furthermore, $3.00/W for silicon would drop to $2.30 or even less.

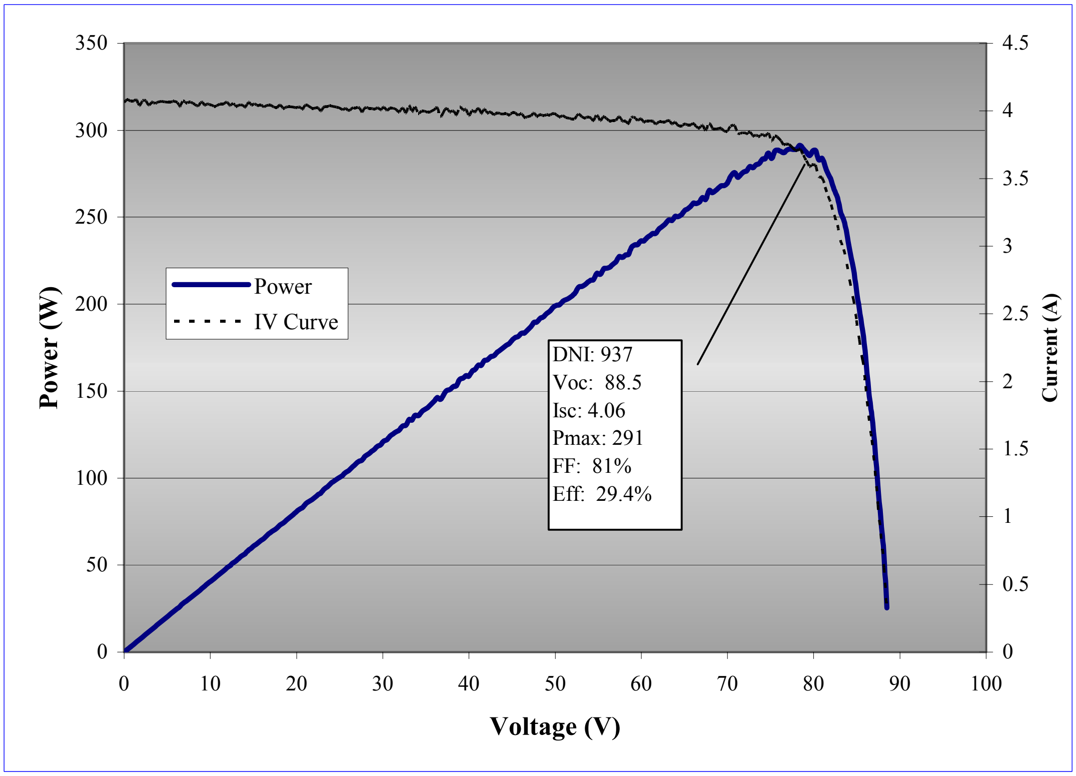

Fig. 1: Power and efficiency properties of the Amonix ~1.0 m^2 MJ Module.

Secondly, not only is the installed cost attractive, but the energy generated can be substantially more for CPV. This is a result of the difference in the manufacturer's typical rating between a concentrator and a flat plate, either crystalline or thin-film, which conveys an inequitable appearance. This bears some explanation.

The established STC rating for a flat plate works well as a reference comparison between various manufacturers, though it is a laboratory metric. It does not include field conditions such as temperature effects, array mismatch affects, DC collection losses or soiling for example. It functions adequately when the customer understands the de-rating factor associated with field performance of an STC rated module. This de-rating factor is not the same for a concentrator system, however, as some of the deleterious field effects are included in its performance rating (PTC). This is especially true for the Amonix system, where the rating of which is an AC rating at PVUSA test conditions. The tracking factor can also make the comparison less clear, see Table 1. This means that in high DNI areas, the kWh/kW generated from an Amonix concentrator is up to 25% more than for a fixed flat-plate (FFP) system of the same installed rating (using STC rating for the flat plate system and PVUSA rating for the concentrator system). This is equivalent to discounting the installed $/W cost by 25%. Thus the $3.30/W installed cost mentioned above would be an equivalent FFP rating of below $2.75/W. Below is a chart of calculated kWh/kW using the NREL Solar Advisory Model (SAM) software for both a concentrating system and a fixed flat-plate system (see fig. 3) A very conservative assumption of a 15% de-rating factor for a fixed flat-plate system and 10% for an Amonix concentrator was used.

Figure 2. A 75 kW installation for Nevada Power in Las Vegas, Nevada. The systems were installed May 2006.

Table 1: Power Waterfall Comparison for STC Fixed Flat plate and Amonix Concentrator system

Field Affect	**FFP factor**	**Amonix Factor**
Soiling	100%	90%
Temperature	90%	100%
Array mismatch	99%	100%
DC collection	99%	100%
Inverter	96%	100%
Tracking benefit	0%	(varied)

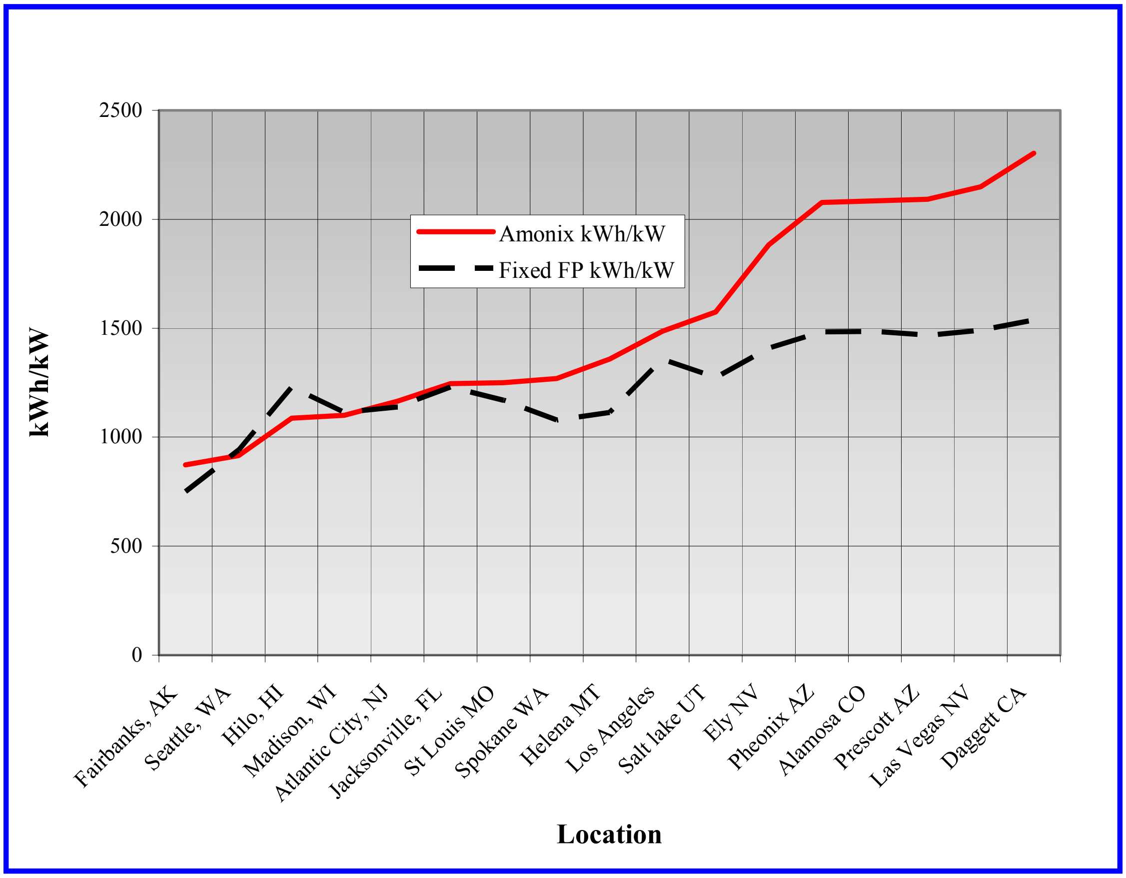

Figure 3. Comparison of the generated kWhs per rated kW: Amonix CPV vs. fixed flat plate for different geographical areas (Solar Advisor Model).

A third potential of concentrators revolves around its premium match for peaking power. It is well advertised that a fixed flat-plate solar system is a good candidate for peak-power matching in areas of high air-conditioning use. However, at least for many areas, it is not a perfect one, as peak loads often extend into the late afternoon and evening hours. Concentrators help in this regard due to their inherent need for and thus benefit of tracking. Below is a summer utility load profile for southern California with a fixed flat-plate array and a concentrating array generation profile superimposed upon it. It is clear that the power generated by CPV falls into the more valuable peaking load market without any added expense due to its inherent tracking. This makes not only the amount of energy generated greater, but also the value of that energy greater (see fig. 3).

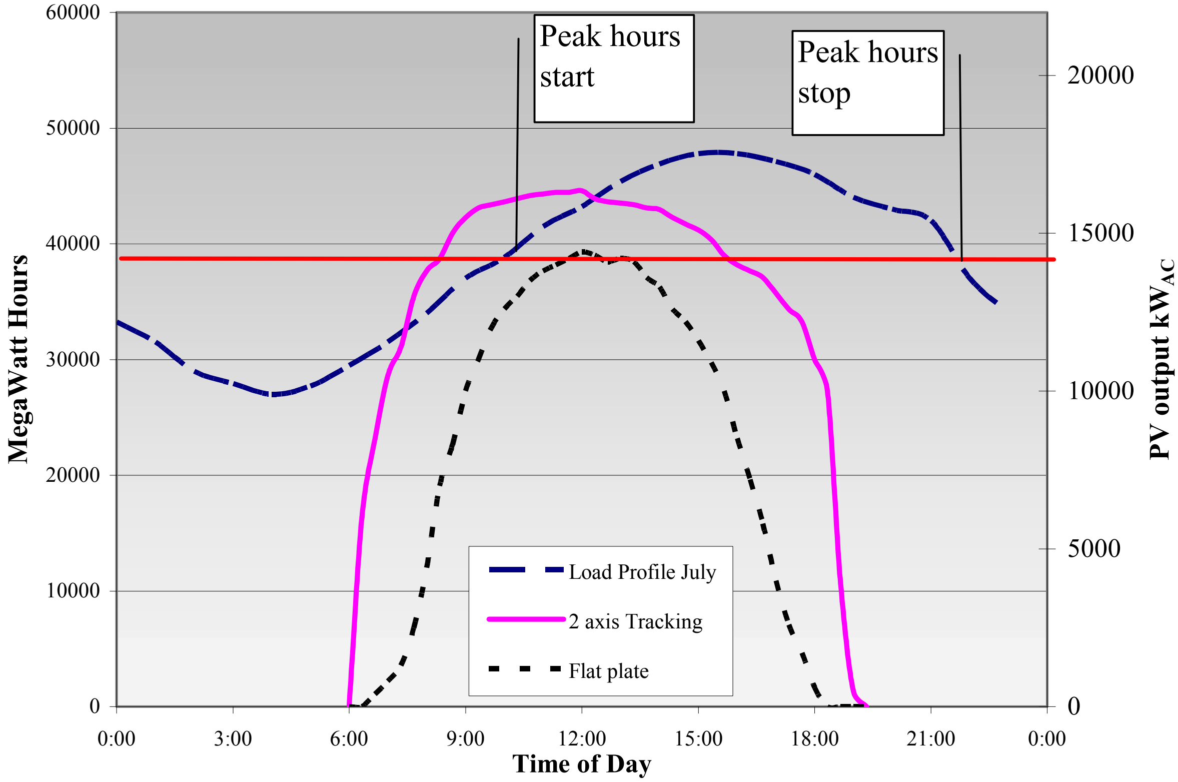

Fig. 3: Cal ISO load profile in July 2006 with PV generation curves (from CAL ISO website). The utility load profile is shown with the typical power output characteristics from both a 2-axis concentrating PV and a fixed flat plate array.

There are still other advantages shown by CPV, that can give it a competitive edge over flat plate under the right circumstances.

- Single crystalline and multi-crystalline silicon are much further along the development curve, so the increase in efficiencies would theoretically be smaller than for the potential for the multi-junction cell. Thus costs benefits associated with today's cells would likely be even greater in the future.
- More of the components in concentrating systems use basic technologies so can be produced in most countries, allowing point-of-use manufacturing, and rapid ramp-up of manufacturing.
- Finally, at least in the case of an Amonix, the system is vertically integrated. Amonix controls the manufacture of the entire array through the tracking and control system. This is a competitive edge in an increasingly competitive industry, minimizing such problems arising from supplier quality, and supply chain management.

With all of this promise, the question remains: why haven't concentrators been a player in today's market? The answer is for several reasons, some of which have been alluded to earlier. Firstly, there has not been the monetary support for its development either through secondary revenue streams or venture capital. Secondarily, a concentrating system is inherently more complex to design than a flat plate system. The design is more multi-disciplinary involving not only semiconductor physics and high end processing, but structural and mechanical engineering, optical engineering, thermal management as well as electronic and electrical engineering. The time to maturation is intrinsically longer for a concentrator. The Amonix experience bears this out. The stable silicon solar cell was a relatively quick milestone as a result of its expertise in that area. It shortly had to jump into the system development both to improve existing technologies and in some cases to invent others. This has taken more time and has not been as smooth. In the case of the multi-junction module, the optical design again had to be modified to match the characteristics of the refractive Fresnel lens to the spectral sensitivities of the MJ cell[3]. Thirdly, as a result of the above reasons, field testing time has been less, hampering the eagerness of the market to take on a higher risk technology. This is especially true for the MJ cell, as they have only been fielded for no more than a few years. Finally, without high volume manufacturing, the development of the custom automation has lagged behind flat-plate. High volume manufacturing in the flat plate industry is well understood and secondary industries have arisen to serve this market. This has not been the case thus far for concentrators, which require similar, but unique none-the-less, automation technology.

That being said, however, the initial roadblocks to full commercialization of concentrators are being removed and the development is now accelerating.

FUTURE OF CONCENTRATORS

A number of players have been diligently trying to commercialize their product. Funding opportunities are on the rise, and projections from each of these players promise high volumes in the near future. Solar Systems Inc. in Australia and Guascor Foton (see fig. 4), Amonix's partner in Spain, have produced in excess of 10 MW of installed, and have a combined production capacity of over 15 MW/year. Others such as Isofoton, Concentrix and Solfocus are still in development. Amonix Inc. is projecting 25 MW/year production output by 2010, with the DOE's help through the Solar America Initiative (SAI).

Fig. 4: Guascor Foton's multi-MegaWatt Installation in Spain.

As a result of its 10 years of field experience, Amonix is in an attractive position for the burgeoning solar market. With its field-tested systems, Amonix expects a rapid ramp-up to the 10 MW level and beyond. Amonix is currently beginning the fulfillment of contracts to retrofit one of its large array modules with multi-junction cells. This will of course provide more needed field experience with the MJ cell, but also provide information on the expected energy generation of the multi-junction cell under real world conditions. Unlike the silicon cell, the multi-junction cell is more sensitive to the changes in the type of sunlight it sees. It is well known that the silicon cell experiences small changes in efficiency with spectral changes in the incoming solar flux. A 'redder' sun in the morning and evening will increase the efficiency of conversion as a larger percentage of the sunlight is in the spectrally ideal area of the silicon's response [4] This dependency on spectral content is amplified in the MJ cell. Affects such as humidity, diffuse light, high air mass number, and circumsolar radiation can affect the efficiency of the cell and thus the energy generation. Therefore determining a kWh/kW number for a year will be more weather and site specific for the MJ system. This type of information will be valuable for projecting the levelized energy cost of the newest MJ systems.

SUMMARY

The arrival of the multi-junction cell captured the attention of many entrepreneurs and venture capitalists as offering tremendous potential for inexpensive solar energy. This latest module produced by Amonix Inc. further underscores the capability of this technology. The exciting part is that the cost projections for the multi-junction CPV systems will drop even further as the multi-junction cell and CPV technology continues to mature. Cell efficiencies should continue to rise. Cell manufacturing costs should decrease due to increased volumes or competition in the industry. Further engineering improvements in the balance of systems such as tracking structures should also enhance cost numbers and increase reliability. All of these dynamics ought to act to further decrease the levelized cost of energy indicating CPV's probable leadership in lowest cost solar energy generation for bulk power.

There is little doubt among experts that solar energy will have a strong niche in the energy demand of the world. What the face of the market will eventually look like remains to be seen. With varied applications available such as remote power and residential markets, small-scale commercial markets and large-scale utility applications, there is room for many types of approaches. Not only that, but in all probability the market will be better served by complementing technologies in the future. CPV will in all likelihood be one of the major players.

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