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Weighing the merits of solar power plants using concentration photovoltaics (CPV)

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ABSTRACT

In endeavouring to introduce its relatively new technology to customers of traditional utilities, the photovoltaic industry often finds itself in the awkward position of trying to sell a product to a customer who may not want to buy. The upfront capital costs of new solar plants (which deliver power only intermittently) can be less than appealing. To facilitate large-scale grid integration there is a need for the development of PV technologies that more closely fit the profile of traditional power sources. In addition to low cost, things to consider include high capacity factors and the ability to better match demand during daylight hours. As a step towards satisfying these requirements, concentration photovoltaic (CPV) power plants are now being integrated into the grid at megawatt scales. By performing light collection using acrylic, silicone or glass optics instead of semiconductors, CPV fundamentally shifts the material cost balance. The world's most efficient solar cells can now be employed, and maintaining tracking of the sun becomes economically favourable across vast sunny locales worldwide. Offering AC system efficiencies in excess of 25%, the resulting CPV power plants produce high energy yields throughout the year and deliver the high capacity factors demanded by utility customers. Since semiconductors are a minority component cost, manufacturing capital costs are lower than for any other PV technology, allowing for rapid scale-up and field deployment. This paper describes the state of the art of CPV technology, field performance results and the outlook for near-term deployments.

Introduction

Upfront capital costs mean that new solar plants, which deliver power only intermittently, can be unattractive as replacements for fossil-fuelled plants. Large-scale grid integration will be accelerated by PV technologies that best fit the profile of traditional power sources. Low dollar per watt cost is thus a necessary, though not a sufficient, condition. Photovoltaic power plants will also need to deliver higher capacity factors and the ability to better match demand, at least during daylight hours, than at present. This suggests the need for tracker-based systems (Fig. 1(a)).

While the benefits of tracking the sun to the horizon have been understood since the earliest days of PV, commercialization of tracking systems has been hampered by the higher upfront costs, operation and maintenance costs, and a market that has often incentivized rated power ($/W) over energy (¢/kWh). As the PV market has reached maturity, emphasis has shifted away from peak power ratings towards energy yield, as reflected in the adoption of feed-in tariffs in Europe, Japan, parts of the USA, China and elsewhere. With an eye on increasing the net cash flow of PV plants, migration towards tracker-based installations has accelerated. Tracker-based PV favours higher-efficiency modules for an energy yield that justifies the higher cost of installation and maintenance. For energy return on a tracker, there is no better technology than high-concentration photovoltaics (Fig. 1(b)).

Concentration photovoltaics (CPV) that operate at high concentration, above about 100×, rely on precise, dual-axis tracking. Such trackers have operated reliably for many years, but the upfront cost was a deterrent until around 2006, when the efficiency of III-V multijunctions reached 40%. Following a trajectory that

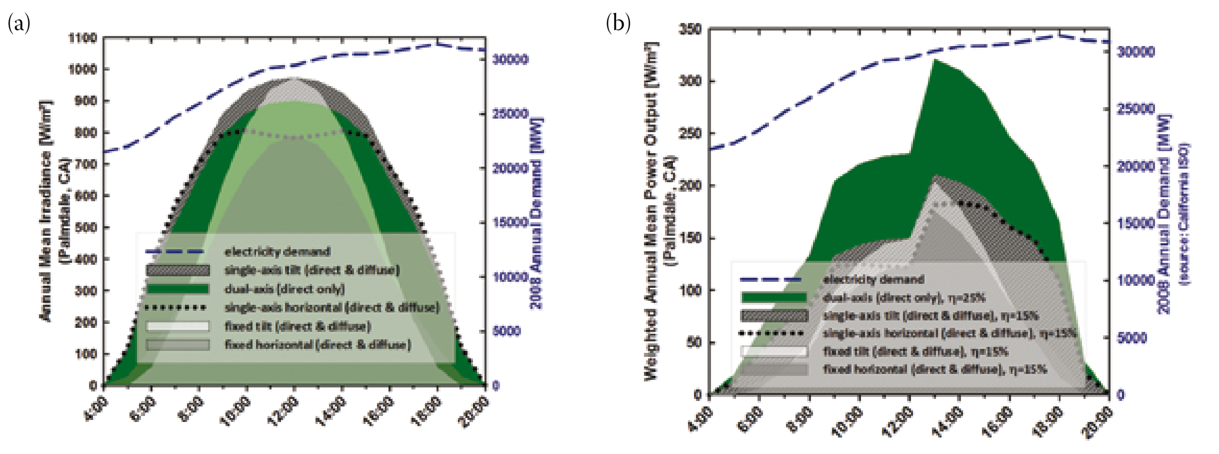

Figure 1. (a) Use of the solar resource to meet grid demand depends on either single- or dual-axis tracking. (b) The benefit is more pronounced if the irradiance is weighted by time-of-day utility rates (source: Southern California Edison) and conversion efficiency is considered. As an illustration, an AC system efficiency of 25% was assumed for dual-axis (CPV) systems and 15% for all other systems.

began more than a decade earlier in space applications, III-V multijunctions then proceeded to displace high-efficiency silicon cells in the CPV systems then under development. The move to III-V multijunctions delivers more than a 30% increase (relative) in AC system efficiency; dual-axis tracking maintains this high efficiency from sunrise to sunset. This combination makes a virtue out of necessity: the higher energy yield more than justifies the cost of dual-axis tracking, as well as the higher cost of the III-V multijunction cells.

Economics

In conventional PV, large sheets of semiconductor material are needed to perform both light collection and energy conversion. The fundamental premise of CPV is that semiconductors need not be used for light collection: lower-cost materials serve this function. Substituting acrylic, silicone or glass optics for semiconductors separates the light collection from energy conversion and fundamentally shifts the cost balance of PV. The world's most efficient solar cells can now be put into service, and precision tracking becomes economically favourable across vast sunny locales worldwide. A dividend of CPV is that cell voltage rises logarithmically with light intensity; this is why cell efficiency increases with concentration. With AC system efficiencies now in excess of 25%, the resulting CPV power plants produce high energy yields throughout the year and deliver the high capacity factors demanded by utility customers. Since semiconductors are a minority component cost, manufacturing capital costs are lowered, allowing for rapid scale-up and field deployment.

"A dividend of CPV is that cell voltage rises logarithmically with light intensity; this is why cell efficiency increases with concentration."

The leveraging effect of efficiency and concentration is illustrated in Fig. 2. Applying cost assumptions for flat-plate and dual-axis tracking at production scales [1], CPV systems using cells with efficiencies of 40% or more are projected to deliver an upfront system cost below the range achievable for flat-plate systems employing single-crystal silicon cells. The outsized role that efficiency plays in CPV also leads to more headroom for innovation: improvements in performance and durability that would otherwise prove too expensive in less efficient designs

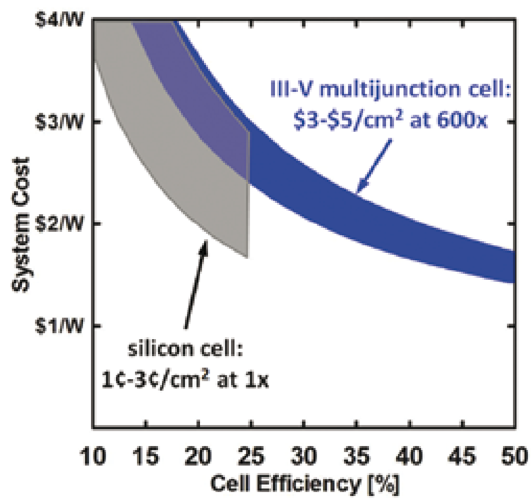

Figure 2. With high efficiency and high concentration, low system costs are achieved despite the high cost of III-V multijunctions. Here, the world-record efficiency of 25% is assumed as an (optimistic) upper bound for commercial silicon cells. 1¢/cm² translates to about 40¢/W at 25% (DC) cell efficiency.

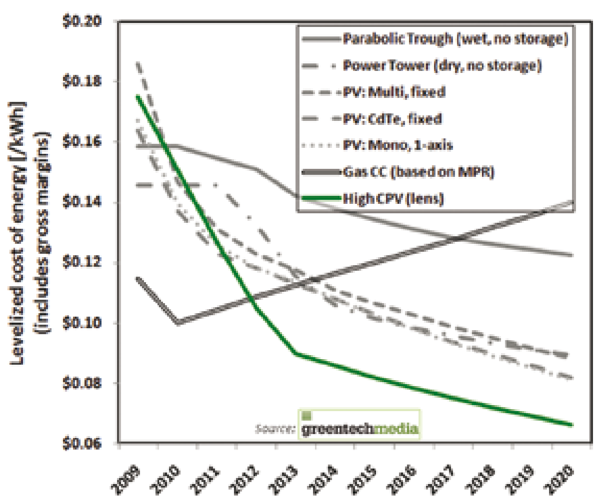

Figure 3. At scale, CPV is expected to outrun rival technologies in delivering the lowest levelized cost of energy (LCOE) [2].

typically pay for themselves in CPV. These advantages have provided the impetus for scaling up production of CPV power plants. Once CPV reaches the scale of other technologies, it is expected to deliver the lowest levelized cost of energy (Fig. 3).

The system economics of CPV favour maintaining the highest possible efficiency, so low cost of energy is obtained by making the most of the III-V multijunction cells. The cells that lie at the core of CPV power plants today are well equipped to take maximum advantage of the energy delivered to them via the concentrating optics. Commercially available cells now realize 40% efficiency under standard test conditions (25°C, 1000W/m^2, AM1.5 spectrum). The temperature coefficient of III-V multijunctions is less negative than for other semiconductors (such as CdTe and Si) and the magnitude decreases with increasing concentration [3]. When paired with properly designed optics, a passively cooled module above 500× concentration readily achieves DC efficiencies over 30% (Fig. 4(a)); AC system efficiencies greater than 25% have been demonstrated by several CPV companies (Fig. 4(b)).

Ratings

The different methods used in rating cell, module and system efficiencies create some confusion. Standard test conditions (STC) of 25°C and 1000W/m^2 are used for the cell, but not for the module. Since CPV optics generally require outdoor (on-sun) testing, both modules and systems are usually measured under operating conditions instead, which are typically taken to be 20°C ambient and either 850W/m^2 (PVUSA) or 900W/

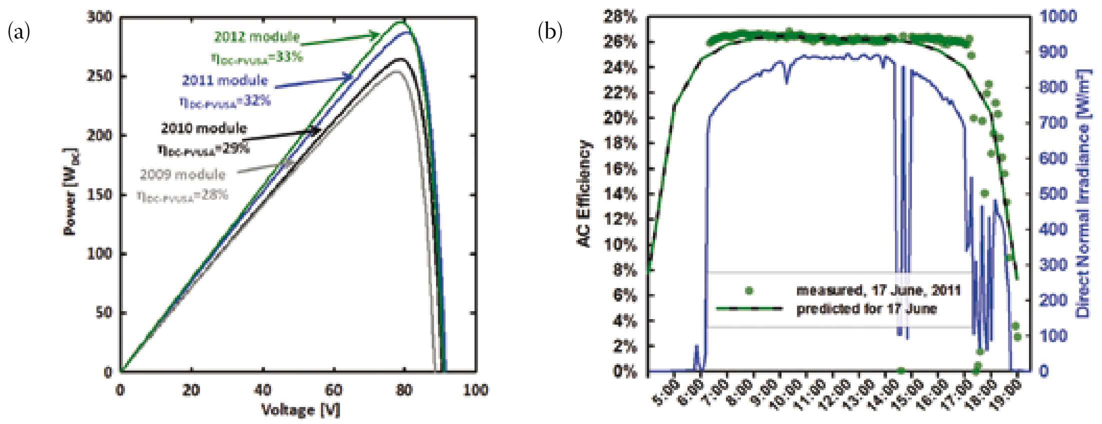

Figure 4. Since the integration of III-V multijunctions, Amonix CPV module operating efficiency (a) and system efficiency (b) have continued to rise steadily. The generator in (b) is a 7700 from the 2MW plant at the University of Arizona Science & Technology Park (UASTP) in Tucson, USA.

m² (IEC 62670, draft). Whereas many installers are accustomed to having PV modules in the field perform below their rating (under STC), CPV systems often perform above their (PVUSA) rating in locations with higher direct normal irradiance (DNI). The difference between standard and operating conditions accounts for about a 7% relative (3% absolute) decrease in rated efficiency from CPV cell to CPV system. The remaining loss is due to transmission and reflection losses from the optical elements, as well as string mismatch and inverter losses. Additional losses arise once real-world variations in the conditions are factored in. In order to translate high cell efficiency into high annual energy generation of a system, the design must balance tradeoffs involving variations in cell temperature, irradiance intensity, irradiance uniformity and spectrum variation. A cell designed for peak efficiency under STC is not likely to be optimized for maximum energy yield under lossy concentrating optics, at elevated temperature, over the course of a day or a year in the field.

Energy prediction and results

To optimize a CPV system for actual field conditions, a predictive energy model has been developed that has proved successful in predicting both peak daily power and cumulative energy generation of existing installations [4,5]. The Typical Meteorological Year 3 (TMY3) database [6], established by NREL, is used as the source for the atmospheric and environmental conditions (air turbidity, precipitable water, ambient temperature, site pressure, etc.) that have an impact on the operation of III-V multijunctions. These inputs are used to generate representative spectra using the SMARTS radiative transfer model [7] (Fig. 5(a)). When combined with the spectral response of a III-V multijunction cell and losses due to the optics, the current available to each sub-cell is determined. Further corrections for the impact of intensity variation and temperature on voltage and fill factor, as well as the various (and variable) mismatch losses, result in a comprehensive, hour-by-hour prediction of CPV system output for any location in the TMY3 database. Though this is essentially a predictive model, a soiling correction based on the cleaning schedule is necessary to give expected peak daily power. For cumulative energy generation, an average soiling rate is sufficient and the model becomes entirely predictive.

This model has been applied to existing installations. The first Amonix generator using III-V multijunctions has been operating since January 2009 in Las Vegas, USA. Fig. 6 shows the effectiveness of the model in predicting the performance of this generator. Despite the vagaries of weather and season, peak power rises and falls much as expected. In Las Vegas, this

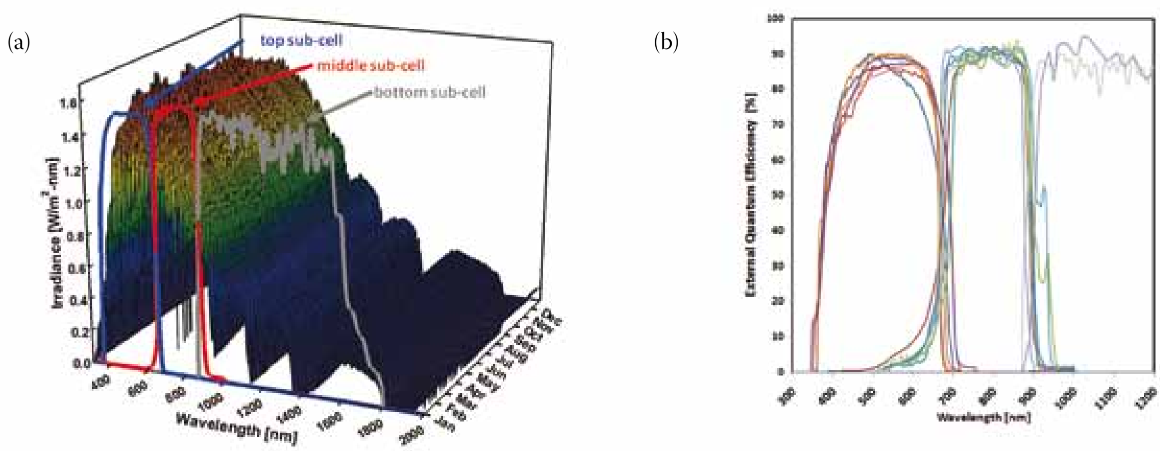

Figure 5. (a) Hourly spectra generated using TMY3 inputs to SMARTS for a year in Las Vegas, USA. The spectral responses of the three sub-cells in a conventional III-V multijunction are also shown. (b) The variety of alloy compositions available provides the means for tuning the spectral response for increased energy generation in the field.

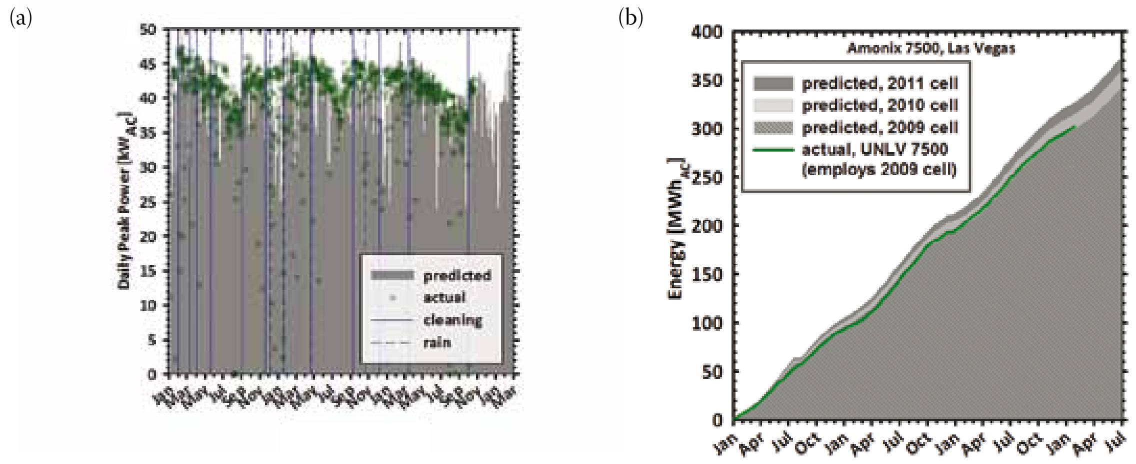

Figure 6. (a) Predicted vs. actual peak AC power of the 38kW$_{AC}$ Amonix 7500 operating in Las Vegas, USA, since January 2009. Actual cleaning and rain events were used to calculate the expected soiling losses in the prediction. (b) Corresponding cumulative energy generation. After more than 3 years in operation, the difference between predicted and actual energy (using 2009 cells) is less than 1%. The average energy yield over three years is 2600 kW-h/kW.

generator also typically operates above its 38kW$_{AC\text{-}PTC}$ rating. After more than 3 years of operation, which is 12% of the warranty lifetime, the cumulative energy is within 1% of the prediction. Any degradation is therefore below the threshold of detection.

Designing for energy yield

The model in question is now being used to predict the energy yield of future power plants and make choices between competing design improvements. Opportunity for improvement has grown substantially in the last two years, as more advanced III-V multijunction designs have become available. The spectral response of III-V multijunctions has, until recently, been a limitation in increasing the energy yield. The spectral response is a result of the alloy composition of the III-V layers, but there is limited latitude for changing this alloy composition without compromising material quality. Fortunately, the accelerating interest in CPV that began in 2006 has germinated a host of new cell designs, from multiple vendors, that are now reaching commercial viability. The confusing mess of spectral response curves shown in Fig. 5(b) is a bounty for the CPV

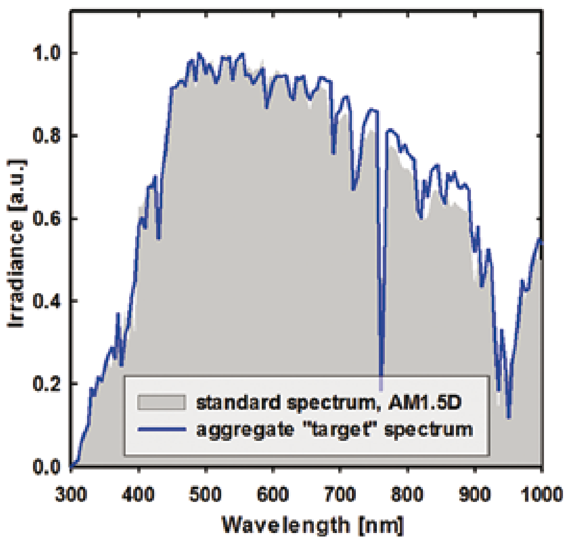

Figure 7. Target spectrum compared with the standard AM1.5D reference. The target spectrum is a composite based on TMY3 data from six locations: Alamosa, CO; Las Cruces, NM; Las Vegas, NV; Palmdale, CA; Tucson, AZ ; and Denver, CO.

system designer trying to squeeze more energy out of the next-generation systems. New designs include metamorphic materials [8], quantum structures [9] and grown bottom sub-cells that provide a higher voltage than the conventional germanium bottom sub-cell [10].

The greater flexibility afforded by these newer structures is already making its way into commercial CPV systems. Fig. 6(b) shows the increase in energy output predicted for an Amonix 7500 with the recent generations of cell designs. The ability to tune the spectrum response delivers a remarkable increase in energy generation with respect to cells available in 2009. Whereas the expected increase in efficiency for the latest cells under standard conditions is about 8% (relative), the increase in energy yield is about 14%. However, even more energy is available, as the current cell structures are still designed for maximum current output under the standard spectrum. Since the spectrum that reaches cells under optics in the field differs from the AM1.5D reference, further increases in energy are expected once cells are re-tuned for field conditions. Taking into account transmission losses from the optics, variation over the day and year in target locations, and weighting of the spectra with typical time-of-day (TOD) utility rates results in a new 'target' spectrum shown in Fig. 7. This composite spectrum is noticeably more 'red rich' than the AM1.5D standard. This implies that a typical III-V multijunction cell, designed for the standard AM1.5D spectrum, will, on average, have insufficient photons available for the top sub-cell. The movement by cell suppliers to re-balance cell structures for field conditions is now underway. Once cells are re-tuned, energy yield is expected to rise an additional 3–6%, depending on the cell technology [11].

Improving the III-V multijunction cell structure is just one of a host of design improvements beginning to reach commercialization now that CPV scale-up has begun. The III-V structure is currently grown on 100mm germanium wafers. The transition to 150mm wafers will take place in 2012, led by cell suppliers such as JDSU and Spectrolab, and will facilitate a cost reduction trajectory familiar in the semiconductor industry. The increase in the packing fraction of the cells, along with a decrease in the proportion of cells near the wafer edge, results in cell yields substantially higher than those corresponding to the 2.25× increase in area (Fig. 8).

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Optics

The optics in CPV systems must satisfy multiple competing demands. The outer optical surface must be highly transmissive over the wide range of wavelengths converted by III-V multijunctions, but also robust under long-term exposure to UV radiation, temperature, humidity, soiling, occasional snow loads and hail, and resistant to abrasion from both windborne particles and cleaning. Two materials that meet these requirements are acrylic and tempered glass. Tempered glass has superior UV stability and abrasion resistance, but typically has lower optical transmission than acrylic. The shaped optic that collects and concentrates sunlight, known as the *primary optical element* (POE), can be either a refractor (e.g. Fresnel lens) or a reflector. In the case of a Fresnel lens, which is the most common POE in use today, the flat side of the lens also serves as the outer optical surface. The POE must have low loss (transmission/reflection above 90%), be formed with precision, maintain its shape under varying temperature and humidity, and be manufacturable at low cost. Reflective POEs are often back-surface mirrors to minimize degradation of the reflective surface, but this approach comes at the price of lower optical efficiency. Reflectors have an advantage over refractors, however, in terms of chromatic aberration, which can reduce the fill factor of a III-V multijunction cell.

Refractive POEs are typically Fresnel lenses, although all-glass convex lenses are also coming into use. Glass is generally too viscous to form the fine ridges needed for high optical efficiency in a Fresnel lens, so Fresnel POEs are composed of either acrylic or silicone-on-glass (SoG). Researchers at NREL have recently published a comprehensive study of the characteristics of Fresnel lens materials as they relate to CPV [12]. Acrylic has the virtues of low cost and high optical efficiency, and a lens composed of a single material experiences less distortion due to mechanical stresses. The principal disadvantage of acrylic is that it has less UV tolerance than glass, but long-term outdoor exposure studies of even the older acrylic materials have so far indicated that degradation rates are modest – less than 0.4% per year. Acrylics developed in the last decade, specifically for long-term outdoor exposure, fare even better. A compensating advantage of acrylic is that UV inhibitors and other additives can be combined with the acrylic backbone to increase UV resistance and enhance mechanical properties.

Newer acrylics now in production promise reduced degradation rates compared to the older acrylics tested in the field, with negligible impact on energy yield. In SoG lenses, the outer surface is glass, an excellent material for surviving long-term outdoor exposure. Antireflective coatings are also easier to obtain on glass than on acrylic. The lens pattern for SoG lenses is formed using UV-resistant silicones. This class of silicones is highly transparent, but relatively soft, so care must be taken to avoid dust accumulation on the inner lens surface. Since the silicone materials have higher expansion coefficients than glass, the silicone lens facets tend to become distorted under temperature. The index of refraction of the silicone also changes. As a result, it is more difficult to maintain optical efficiency; highest efficiency is maintained by keeping the area of the lens elements relatively small. Long-term adhesion of silicone to glass must also be verified. Based on these tradeoffs, acrylic lenses remain the component of choice for Amonix generators. However, SoG lenses are a viable option for regions susceptible to sandstorms, for example.

In addition to the primary optical element, most CPV systems employ a secondary optical element (SOE). (Some systems even employ a tertiary optical element, but the optical losses of the additional optical 'bounce' are often prohibitive.) The SOE can be reflective or refractive, and is either in close proximity to, or in contact with, the surface of the cell. Reflective SOEs often function merely to increase the acceptance angle of the system by reflecting back light that strays off the cell aperture area. Refractive SOEs, on the other hand, can be designed to increase concentration and improve flux uniformity within the aperture, which increases the fill factor of the cell. From a pure performance standpoint, refractive SOEs are therefore superior. However, they are more expensive, and direct contact to the cell surface requires more delicate assembly. The adhesive must be strong enough to ensure a stable optical interface for the design life, yet compliant enough to avoid cracking the cell during temperature excursions. Whereas gradual soiling of a reflective SOE has a modest impact on performance, soiling of a glass SOE can lead to stress cracking that would compromise both the SOE and the cell.

Manufacturing and installation

Once these components are assembled into a module, high energy yield depends on precise tracking. Most high-concentration systems have an 'acceptance angle' of less than one degree. Should the module veer off track by more than this value, power loss would be in excess of 10%. Systems that deliver high energy yield are therefore designed to maintain their pointing vector to within a few tenths of a degree of the solar disc. This can be obtained with either electric gear drives or hydraulics. Gear drives may have lower upfront cost and require less routine maintenance, but often produce substantial backlash during tracking and reduced precision over time as the gears wear out. Hydraulics are generally favoured for larger systems and allow for rapid movement into stow position during wind gusts, for example.

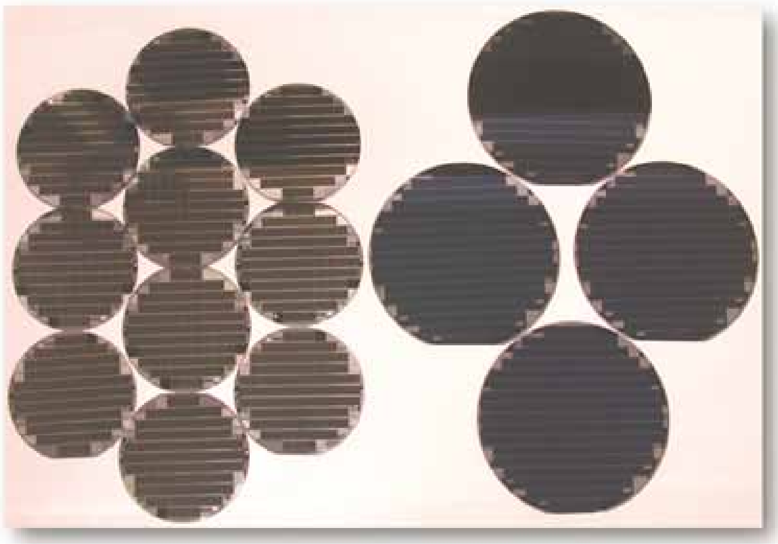

Figure 8. The four 150mm wafers (right) contain the same number of cells as the ten 100mm wafers (left). Processing cost per cell is reduced, packing fraction is increased and the lower perimeter-to-area ratio results in higher yields.

"Once these components are assembled into a module, high energy yield depends on precise tracking."

Amonix generators offer one illustration of CPV for utility-scale power generation. The Amonix 7000 series is the seventh generation, but marks the first use of III-V multijunctions at Amonix. Design improvements in the cell and the rest of the power path have led to a 20% (relative) increase in efficiency since the first 7700s were installed using III-V multijunctions just two years ago. DC module efficiency now

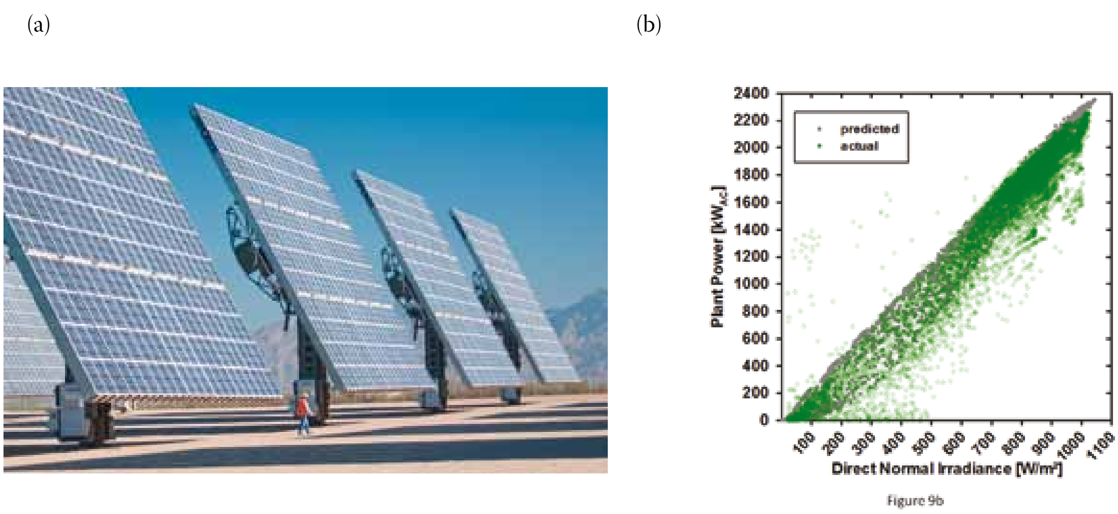

Figure 9. (a) Five of the thirty-six generators that make up the 2MW installation at UASTP in Tucson, USA. (b) After six months of operation, the plant output closely matches prediction from the energy model.

exceeds 33% under operating conditions (Fig 4a). Almost twice the size of any other PV system, the 7700 relies on hydraulics for its tracking. The MegaModule design reduces material and installation cost by ganging thirty-six module-sized components into a single rigid frame. Each MegaModule brings $10kW_{DC}$ into alignment at once and is mounted using four connection points. Most assembly is therefore relocated back to the level of MegaModule construction, in the controlled environment of a CPV factory. Since the semiconductor component is substantially reduced, a CPV factory is relatively low tech. New factories can be put into operation in just a few months, close to point of use, and at a fraction of the capital cost of technologies that are weighted more heavily by the semiconductor components.

Similar to other large-scale construction projects, installation of the CPV systems is highly mechanized. In the Amonix case, cranes now hoist about $70kW_{DC}$ into position with each array of seven MegaModules; megawatts can be installed in a day. This is a substantial advantage, particularly in remote locations, for an industry in which installation can make up the majority of the project cost. Panels mounted high off the ground also enjoy lower soiling rates. Wind buffeting can reduce energy yield, but the effects of wind loading in most target locations have been found to be acceptable. Compared to installations mounted close to the ground, CPV has a smaller effective footprint: it requires less site preparation and has a lower environmental impact during operation.

More than half a dozen CPV installations with individual capacities of over 1MW each have been commissioned in Europe and the USA by companies such as Amonix, Guascor Foton, Soitec and SolFocus [13]. All the installations since 2007 have employed III-V multijunction cells. One such recent installation is the Amonix plant at the University of Arizona's Science & Technology Park (Fig. 9(a)). The 2MW plant consists of thirty-six 7700s rated at $56kW_{AC}$. The performance of the plant, in operation since June, matches prediction (Fig. 4(b), Fig. 9(b)). A fall-off in peak power relative to prediction observable at levels of direct normal irradiation greater than $900W/m^2$ is primarily due to coincident temperatures that exceeded 40°C around solar noon during the summer. With more than a hundred generators online, Amonix now has over 100 unit-years of operating experience with III-V multijunction systems and will soon be adding more than a unit-year per day. A 30MW plant under construction in Alamosa, CO, will consist of the latest 7700 generators, rated at $60kW_{AC}$ each and expected to reach AC efficiencies of 27%.

Conclusion

Recent CPV installations signal the commercial scale-up of an industry which is just beginning to gain economies of scale and travel down its experience curve. The high performance of existing systems represents merely the leading edge of a host of improvements already in the transition to production. CPV provides unparalleled energy generation that makes it ideal for deployment in the vast sunny and dry regions of the globe. The continuing installation of large-scale CPV power plants will accelerate the growth of photovoltaics in the world's energy mix.

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