Correspondence

Editorial: Toward 100 Gigawatts of Concentrator Photovoltaics by 2030

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***Abstract*—In this editorial, we report on the conclusions of a concentrator photovoltaics (CPV) industry group convened in July 2012 to develop pathways to large-scale CPV deployment, specifically targeting the installation of 100 GW of CPV in the United States by 2030. The group identified technical and financial barriers to this goal and developed a corresponding set of recommendations for overcoming these barriers. These recommendations focus on technical improvements at the system and cell levels and on activities needed to support the commercialization.**

***Index Terms*—Commercialization, concentrator photovoltaics (CPV), cost modeling, multijunction cells, optics, reliability, tracking.**

I. Introduction and Objective

Concentrator photovoltaics (CPV) [1]–[4] offers the potential to provide the lowest-cost solar energy in regions such as the U.S. Desert Southwest, where the solar resource is enough to satisfy the entire energy needs of the nation many times over. However, advances are still needed to make CPV the clear choice for power generation in such regions. To define the required advances, a technology roundtable brought together key stakeholders (see the Appendix) from the private sector, academia, and government in July 2012 to address technical and cost/market issues for both cells [4], [5] and systems, focusing largely on high-concentration ($\geq$500 suns) CPV. The roundtable's ultimate goal, set in the context of the U.S. Department of Energy SunShot Vision Study [6] projecting PV's role in the U.S. energy supply, was to identify recommended steps for CPV to supply 100 GW of solar electricity in the United States by 2030. This editorial presents these recommendations.

II. Opportunities for Concentrator Photovoltaics

A. Value Proposition

CPV uses low-cost, large-area components—glass, plastic, and metal—to concentrate the dilute solar resource onto a solar cell with about twice the conversion efficiency of conventional flat-plate cells. That greater efficiency reduces the overall collector area, and thus, the cost of the large-area components of the PV system. This cost reduction is a feature of CPV not shared by nonconcentrating PV, because the glass, plastic, and metal that form a significant part of the cost of a PV system are commodity items unlikely to be reduced in cost by increased production volume. Using the standard direct spectrum with 900 W/m^2 available to CPV systems (compared with the 1000 W/m^2 in the standard global spectrum), today's 30% efficient CPV modules generate 35%–170% more energy per module area than 10%–20%-efficient flat-plate modules. This comparison is even more favorable to CPV if the flat-plate modules are fixed and not tracking. A 40% efficient CPV module, which is achievable with sufficient cell and optical system research, would generate 80%–260% more power than 10%–20% flat-plate modules of the same area.

B. Concentrator Photovoltaics Deployment

The deployment of solar technologies is influenced significantly by local solar resources, as well as by electricity prices. CPV works best in geographic regions with high direct-normal irradiance (DNI). Regions with the highest DNI also have the highest available solar resource overall. Thus, they are likely to be where PV electricity generation will first become cost competitive with conventional power sources in the absence of subsidies, depending on the local cost of conventionally sourced electricity [7]. Near-term CPV systems using today's 40% efficient cells may be cost competitive in areas with greater than 6–7 kWh/m^2/day of direct sunlight, a vast area that includes most states in the southwestern U.S. With higher cell and system optical efficiencies, CPV systems can become cost competitive in areas with lower solar resource.

Prior to 2011, individual CPV installations were on the scale of tens to hundreds of kilowatts, with several reaching the 1-MW mark. 2011 saw the largest CPV operation to date—a 30-MW field installed in Alamosa, CO, USA. Worldwide, more than 40 MW were installed in 2011, and more than 50 MW in 2012 [2].

III. Concentrator Photovoltaics Technology Status and Challenges

A. Optics

In CPV, concentration of sunlight is accomplished by optics in one of two general ways. Reflective optics uses various geometries (e.g., dishes or heliostats) of mirrored surfaces to focus light. Refractive optics uses lenses, typically a Fresnel lens, made of glass, plastic, or some combination such as glass and silicon polymer. Secondary optical elements are often used to improve the acceptance angle, maintain uniform irradiance on one cell, or distribute the light between multiple cells. The optics must withstand abrasion from wind-blown dust and periodic washing for cleaning of the optics, and resist yellowing or embrittlement over decades of operational lifetime. CPV optics presents many possible power losses that must be mitigated. Additionally, CPV uses only the direct component of sunlight, whereas flat-plate systems can also use the diffuse component in the global solar spectrum.

B. Trackers

High-concentration CPV requires two-axis tracking. Trackers must be robust against mechanical and wind loading, accurately follow the

Manuscript received October 17, 2012; revised May 3, 2013; accepted June 11, 2013. Date of publication July 5, 2013; date of current version September 18, 2013. This work was supported in part by the U.S. Department of Energy under Contract DE-AC36-08GO28308 to the National Renewable Energy Laboratory.

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Digital Object Identifier 10.1109/JPHOTOV.2013.2270341

position of the sun, and maintain an accurate orientation toward the sun. The higher the concentration, the more stringent the required pointing accuracy, typically in the range of less than 1° pointing accuracy for 500–1000x concentrators, and consequently, the higher the cost of trackers and module structure.

C. Cells

To convert the focused light to electricity, CPV systems use multijunction solar cells, which are the highest efficiency (albeit most expensive) cell architecture. Multijunction cells convert different energy regions of the solar spectrum with junctions whose bandgap is tuned to that energy region. All commercially viable high-efficiency multijunction cells to date are fabricated from III–V alloys, deposited by metal-organic vapor-phase epitaxy or molecular-beam epitaxy on GaAs or Ge. Several structures have demonstrated efficiencies above 40%, nearly double that of the best silicon cell, and efficiencies approaching 50% are likely within the next decade. Multijunction cells are ~100–1000x more expensive on a $/cm^2 basis than the single-junction cells used in flat-plate systems, with present costs on the order of $5/cm^2. However, the cell cost as a fraction of system cost is reduced by the ~500–1000x concentrating factor. Higher efficiency reduces the cost of not only the cell, but also, of the optical, encapsulation, and mechanical support components, i.e., essentially the entire CPV system.

D. Cell Cooling

Efficient cell cooling is required for high-concentration CPV. Thermal conduction to a large surface cooled by natural convection is widely used and is reliable, but can lead to large module size. Heat transfer by liquid-coolant flow to a radiator allows the use of small, high-power modules that may be less expensive to manufacture, at the expense of increased complexity and cost associated with circulating the coolant.

E. Balance of the System

Typical balance-of-system components, similar to flat-plate PV, include inverters to convert the dc electricity into ac, structural frames and supports for the CPV modules (e.g., pedestals), the tracking mechanism and control, active cooling if used, and electrical wiring.

IV. Financial Barriers to Large-Scale Deployment

Several factors combine to challenge CPV industry growth. CPV suppliers often have limited financial resources. CPV systems typically require unique, large-scale, module-assembly facilities with relatively high upfront costs, necessitating bank financing to develop. And CPV's bankability, the ease with which a developer may acquire needed financing from a bank for a specific project, is perceived to be low due to the paucity of available data (compared with flat-plate PV, especially silicon-based PV, which has been well established for decades) on reliability and performance for actual fielded components and systems over at least a several-year period. The lack of an extensive and deep track record and learning curve leads to uncertainty about the technology's potential, degree of risk, and unclear return on investment, so that bankability requirements are not as well defined as for flat-plate PV projects. Furthermore, banks are increasingly reluctant to take on engineering, procurement, and construction related risks and may require a larger margin when contemplating making investments in the CPV technology. Consequently, CPV developers face challenges in acquiring financing.

V. Overcoming the Barriers

Our recommendations focus on improvements to systems and cells, and reduction of barriers to the commercialization.

A. System-Level Improvements

1) *Standard Reference CPV Model System:* Currently, each CPV company has a different bill of materials, and few back up their projections of low costs with documented breakouts of those costs. We recommend development of a reference CPV system for a detailed cost analysis and adoption of standardized methodology for financial reporting. The model system would specify key aspects, e.g., type of cell, concentration ratio, optics, and tracking, which allow a detailed breakdown of target costs for components, as well as installation, and operations and maintenance. The model system would, thus, facilitate a financial analysis of the cost drivers for CPV electricity, which could then be compared with flat-plate silicon PV.
2) *Reduce Component Costs:* Recommendations for specific cost-reduction targets include reducing the costs of Fresnel lens optics from ~$85/m^2 today to $35/m^2 in 2030 and of module costs other than the primary optics and cells from ~$350/m^2 today to $100/m^2 in 2030. Dramatically lower cell costs could also enable systems with lower concentration ratios (100x–200x), which should have lower-cost primary optics, support structures, and tracking systems. A roadmap to reduce cell costs to $3/cm^2 by 2020 and $1/cm^2 by 2030 would help concentration ratios below 500x to become cost effective. Reduction of tracker costs can also significantly lower CPV system costs. Further, an improved understanding of the tradeoff between the accuracy of the tracker in following the sun and the cost of the tracker would be valuable, because relaxing the required accuracy allows for a less expensive system due to lighter structures needing less steel, as well as lower maintenance costs. Such analysis may contribute to the development of a sub-500-sun CPV system.
3) *Leverage the LED Industry:* The CPV industry should better leverage methodologies from the more mature LED industry. For example, LEDs are packaged in a well validated, consistent manner regardless of manufacturer, leading to greater standardization and ease of use. We recommend that CPV systems companies and cell manufacturers develop a standard cell-packaging approach, with a 25-year manufacturer warranty. LED experience may also be leveraged in the areas of reliability and in developing automated deposition tools for reduced manufacturing costs.
4) *Strengthen Evaluation of the Long-Term System Performance:* The United States should develop an organization that functions in similar fashion to the Institute for Concentration Photovoltaics Systems (ISFOC), an institution owned and operated by a Spanish public/private partnership that operates and maintains various demonstration plants that use different technologies, and has fully equipped laboratories to test different plant components. Such a US-ISFOC would support the gathering of data on actual MW-scale systems that could be shared with the entire CPV industry, helping to improve CPV bankability. This activity would be in coordination with the equally crucial industry wide gathering and sharing of long-term reliability and energy production data on full-size fielded CPV systems.

   Accelerated testing in CPV configurations and materials should be expanded using National Renewable Energy Laboratory's (NREL) Reliability group, with results then related back to actual field experience. In government/industry partnerships, regional test centers should increasingly be used to establish

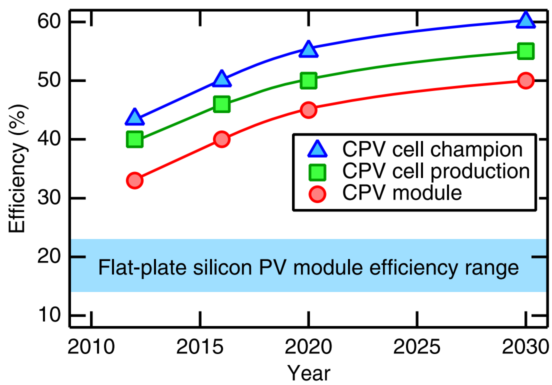

Fig. 1. CPV actual 2012 and targeted 2016, 2020, and 2030 (champion and production) cell and module efficiencies. Flat-plate silicon efficiencies are also indicated.

reliability and energy production of CPV components and systems. DOE's newly created Regional Test Centers could provide such a vehicle for field demonstrations and testing toward bankability.

5) *Reduce the Cell-to-Module Derating Factor:* A key limiting factor in the performance (and related cost) of many present CPV systems is the power loss due to the optics, often referred to as the optical derating factor. Derating factors of 30% are typical. We recommend targeting a 10% derating factor by 2030. Furthermore, industry wide standardization in the definition and measurement of the derating factor is needed.

B. Cell Improvements

1) *Accelerate Cell Efficiency Increases:* Cell efficiency is highly leveraging in CPV, and the multijunction cell technology has much headway for future improvements. Proposed target efficiencies for both champion and production cells (at today's costs) through 2030 are given in Fig. 1. It is also critical to define and quantify opportunities that would be created by decreasing the cell cost. It is likely that next-generation multijunction cells will achieve significantly higher efficiencies than today's commercial three-junction cells by implementing additional junctions, coupled with a range of additional advances. The benefits of these advances will require validation in the field. It will also be desirable to develop improved measurement techniques with reduced uncertainty at the cell and module level; this advanced measurement capability is particularly valuable for cells with an increased number of junctions.

2) *Investigate Alternative Substrates and Substrate Reuse:* Development of substrates providing low-cost and high-quality epitaxy of the multijunction materials would be valuable. Alternatively, the cost of high-quality GaAs or Ge substrates may be greatly mitigated by implementing epilayer removal and substrate reuse, if the cost of these processes can be made sufficiently low.

3) *Develop Monolithic Deposition Options:* Improved understanding of the kinetics of III–V growth, including the physical limits of deposition rates, will enable improvements in material quality and cost; depositional tools with multiple chambers for in-line processing, and leveraging techniques from the flat-panel display industry, can provide higher throughput. Improved and expanded capabilities for monolithically growing dissimilar materials—e.g., nitrides and the conventional III–V—could enable extremely high-efficiency future-generation cells.

4) *Pursue III–V/Silicon Design:* The use of silicon substrates could bring down costs of multijunction cells if long-standing challenges related to III–V/Si heteroepitaxy can be addressed. These include mitigation of threading dislocation density in the III–V epilayers, a challenge that has been largely addressed through engineered buffer layers. A further challenge, the coefficient of thermal expansion mismatch between Si and typical III–V materials, must be addressed, too.

5) *Develop Commercially Viable Mechanically Stacked Cells:* Because mechanical stacked cells can combine junctions made from different materials systems that cannot be grown monolithically, this approach may enable cell architectures that more efficiently convert the solar spectrum.

C. Activities Needed to Support the Commercialization

1) *Standardize Accelerated Testing Protocols:* In contrast with flat-plate PV, where there may be decades of field data, CPV has very limited data, which demonstrate correlations between accelerated tests and failures in the field. We recommend the development of industry standard terminology, definitions, and accelerated test protocols to predict and demonstrate the reliability of CPV products, in collaboration with national laboratories and international standards-writing organizations. This will aid product development and bankability.

2) *Validate Reliability of Components to Guide the System Design:* An industry standardized understanding of the material properties needed for a reliable CPV product (e.g., the comparative properties of plastic and silicon-on-glass-based Fresnel lenses) would narrow the design space and greatly speed product development. This would emulate the development currently underway by the flat-plate community of a suite of test standards to characterize all of the materials used to fabricate PV modules.

3) *Improve CPV Energy Yield Modeling:* Energy yield for CPV modules shows a stronger dependence on spectrum than for single-junction flat-plate PV. The CPV community lacks an industry standard method to determine a nameplate rating and to predict the energy output of a CPV system over the course of a year. For this purpose, we recommend that the DOE Regional Test Centers be used to collect detailed data including measurements of the solar irradiance, as well as spectral content and clouds, as a function of atmospheric conditions. DOE's system advisor model (SAM) has been extended to allow users to consider CPV scenarios. However, the model would benefit from upgrades to better predict the CPV performance to within an accuracy of $\pm 1.5\%$. The improved irradiance data should be combined with a more accurate model for energy production from multijunction cells. In addition, the SAM model should be better validated by actual industry data from the field.

4) *Expand the CPV Community:* Collaborative discussions among CPV manufacturers should be conducted on a regular, continuing basis; new stakeholders such as the U.S. Department of Defense should be invited into these discussions; CPV discussions at major PV venues should be further developed; and CPV could be emphasized as part of the IEEE PV Specialists Conference's focus on reliability and field deployment of solar systems.

VI. Conclusion

CPV presents both great opportunities for low-cost electricity and significant challenges inherent in a technology that has not yet achieved large-scale deployment. A variety of steps are identified, including refinement and standardization of the technology, to address these challenges and to facilitate large-scale commercial implementation.

APPENDIX
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ACKNOWLEDGMENT

The roundtable was co-hosted by UC Santa Barbara's Institute for Energy Efficiency and the Center for Energy Efficient Materials (an Energy Frontier Research Center funded by the Department of Energy, Office of Basic Energy Sciences) and was sponsored by the U.S. Department of Energy and the National Renewable Energy Laboratory.

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