Cost Analysis for Flat-Plate Concentrators Employing Microscale Photovoltaic Cells

Scott Paap, Vipin Gupta, Jose Luis Cruz-Campa, Murat Okandan, William Sweatt, Bradley Jared, Ben Anderson, Greg Nielson, Anna Tauke-Pedretti, Jeff Nelson

Sandia National Laboratories, Albuquerque, NM 87185 and Livermore, CA 94550 USA

***Abstract* — Microsystems Enabled Photovoltaics (MEPV) is a relatively new field that uses microsystems tools and manufacturing techniques familiar to the semiconductor industry to produce microscale photovoltaic cells. The miniaturization of these PV cells creates new possibilities in system designs that may be able to achieve the US Department of Energy (DOE) price target of \$1/W$_p$ by 2020 for utility-scale electricity generation.**

In this article, we introduce analytical tools and techniques to estimate the costs associated with a concentrating photovoltaic system that uses microscale photovoltaic cells and miniaturized optics. The overall model comprises the component costs associated with the PV cells, concentrating optics, balance of systems, installation, and operation. Estimates include profit margin and are discussed in the context of current and projected prices for non-concentrating and concentrating photovoltaics. Our analysis indicates that cells with a width of between 100 and 300 µm will minimize the module costs of the initial design within the range of concentration ratios considered. To achieve the DOE price target of \$1/W$_p$ by 2020, module efficiencies over 35% will likely be necessary.

***Index Terms* — photovoltaic systems, silicon, costs, modeling, photovoltaic cells.**

I. Introduction

The US Department of Energy (DOE) has set an aggressive price target (including profit) of \$1/W$_p$ for utility-scale solar energy installations by 2020 [1]. While non-concentrating photovoltaics (PV) and concentrating PV (CPV) are moving towards this target [2, 3], significant obstacles remain for both technologies. In the case of non-concentrating PV, module efficiencies of 10-22% translate to higher balance of system (BOS) costs per Watt for the installed system. CPV enables the use of higher efficiency modules, but incurs significant additional costs for the tracking and optical systems. Microsystems-enabled photovoltaics (MEPV) miniaturizes photovoltaic cells to potentially reduce BOS costs while still taking advantage of lower cell costs that accompany the use of concentrating optics [4].

The MEPV system architecture consists of hexagonal photovoltaic cells with maximum vertex-to-vertex distances between 100 µm and 1000 µm (Figure 1a) placed on a substrate containing integrated circuitry, to which an optical system comprising a plastic lens stack beneath a glass front sheet is bonded (Figure 1b). This design offers a path to lower module costs through materials minimization, semiconductor processing, and microelectronics assembly. Small cell sizes and moderate concentration ratios of 50X to 200X also result in modules of similar thickness to conventional non-concentrating PV, enabling the use of non-concentrating PV BOS components and installation procedures. In addition, concentrating optics enable the use of high efficiency PV cells to increase the energy output of the system, effectively decreasing the per-watt cost of the remaining components.

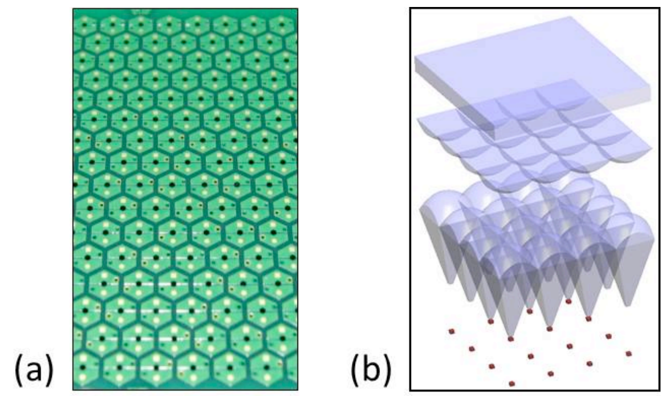

Fig. 1. (a) MEPV cell array for prototype concentrating system. The array consists of 216 microscale c-Si PV cells where each cell is 720 microns wide and 20 microns thick. Each black dot is one PV cell (b) Conceptual illustration of solid MEPV concentrating optics.

We present a framework and method for cost analysis that is employed to guide the design of MEPV systems as well as estimate system price under various sets of input parameters. Such analysis provides an understanding of key cost drivers, and enables an exploration of specific ways to realize future cost reductions. The modeling framework is employed to determine the optimal cell size and concentration ratio of current design concepts, as well as investigate the trade-offs between cost and energy output associated with the use of more expensive fabrication techniques to obtain higher cell efficiency in future designs.

III. Cost Modeling Approach

The overall cost modeling framework consists of modular components representing the solar cells, optics, and BOS (including installation). The sum of these components represents the total installed system cost, which together with operation and maintenance costs is utilized in a calculation of the levelized cost of electricity generated by the system (Figure 2).

$$\mathrm{LCOE} = \frac{\mathrm{NPV}\left[\boxed{\text{Module Cost}} + \boxed{\text{BOS Cost}} + \boxed{\text{Tracker Cost}} + \boxed{\text{Installation Cost}} + \boxed{\text{O\&M Cost}}\right]}{\mathrm{NPV}\left[\boxed{\text{Energy generation}}\right]}$$

Fig. 2. Conceptual representation of the calculation of LCOE. NPV refers to the net present value of the quantities in parentheses.

In addition to being a new PV cell technology, MEPV is also a novel module design approach that can be used to reduce each cost component in the LCOE numerator to the level of non-concentrating PV and increase the electricity generation in the LCOE denominator to the level of concentrating PV. Table 1 shows how MEPV technology development can bring LCOE down in a systematic way.

Table 1. Impact of the MEPV approach on components of the LCOE equation.

PV Component	MEPV Approach
Module	Reduce module cost relative to CPV with microscale PV cells, miniaturized concentrating optics, and microelectronics assembly tools and techniques
BOS	Reduce BOS costs relative to both PV and CPV by using up to 370,000 cells/m^2 to produce high voltage output, eliminating DC-to-DC converters and thicker, more expensive wiring
Tracker	Reduce tracker costs relative to CPV through micro-optical designs with acceptance angles that permit the use of coarse, dual-axis trackers for non-concentrating PV
Installation	Reduce installation costs relative to CPV by producing flat plate MEPV modules that are as easy or easier to pack, ship, handle, hoist, and mount as one-sun PV panels
O&M	Reduce O&M costs relative to CPV and tracking one-sun PV by using MEPV to simplify the overall design, enhancing system reliability, weather-resistance, and autonomy
Electricity Generation	Increase energy generation relative to PV (and CPV in future designs) by boosting the efficiency of the MEPV cell stack and reducing losses in the optical system, tracker, sunlight-to-DC conversion, and DC-to-AC conversion

The MEPV cell technology and module architecture together represent a fundamental shift that impacts not only the module costs, but also every other cost component in the LCOE equation. The thinness and moderate concentration ratio of the modules enable lower component, infrastructure, and labor costs associated with non-concentrating PV, while matching or exceeding the energy generation of traditional CPV systems. Thus, the cost of producing the MEPV modules is the key factor in determining the economic viability of this technology (see Table 2).

A. Photovoltaic Cells

The photovoltaic cells considered in the first MEPV cost model are single-junction silicon cells produced using standard integrated circuit (IC) fabrication techniques. Each of the 64 steps in the production process was modeled based on cost contributions from raw materials, equipment, labor, maintenance, facilities, and consumables. For a 200 mm Si wafer, the total processing cost to yield the final cells was $164 per wafer; this can be viewed as a high estimate, as the process to fabricate solar cells requires equipment with higher tolerances than is necessary for producing modern ICs. Each cell is approximately 20 μm thick, enabling the reuse of silicon wafers over 13 cell production cycles. Cell efficiency is estimated to be 19% for the analysis presented here.

Table 2. Comparison of the components of LCOE for non-concentrating PV, CPV, and MEPV technologies.

Component of LCOE	PV	CPV	MEPV
Module Cost	Low	High	TBD
BOS Cost	Low	High	Low
Tracker Cost	Low	High	Low
Installation Cost	Low	High	Low
O&M Cost	Low	High	Low
Energy Generation	Low	High	High

B. Optics

Solar radiation is concentrated on the individual cells within a module through a pair of polycarbonate (PC) lens arrays (Figure 1b). The outer lens is bonded to a front sheet of low-iron glass, and the space between the lens arrays is filled with poly-dimethylsiloxane (PDMS) to prevent ingress of moisture. The cost model for the mass production of lenses is based on injection molding and was developed using the approach of Baumer and Makinen [5]. Estimated materials costs of solar glass and both plastics were obtained through direct inquiries to vendors. Optical efficiency of the lens stack is estimated to be 96% based on physical modeling.

C. Module

The module production process includes steps to transfer the solar cells from wafers to a polyamide substrate containing integrated circuitry, apply a polyvinyl fluoride backsheet, position the lens assembly over the cells, seal the module edges, and attach the junction box. Cell placement - the transfer of cells from silicon wafers to the module substrate - is accomplished using a commercial pick-and-place tool. Electrical connections between the individual cells and the integrated circuitry of the substrate are made using solder bumps.

Materials costs were obtained from a recent analysis by researchers at the National Renewable Energy Laboratory (NREL) [6] and through inquiries to vendors. Module assembly steps for the production of crystalline silicon PV modules were applied directly to MEPV module production, with the exception of those related to cell assembly and busing; estimated costs for these process steps were also taken from the recent NREL paper [6]. Estimates of additional costs for the cell placement and solder bumping steps were obtained directly from equipment vendors and service providers.

D. BOS and System Installation

The concentrating optics design and moderate concentration ratios selected for the MEPV system result in an acceptance half-angle of approximately three degrees — considerably larger than that for a typical high-concentration PV (HCPV) system. This enables the use of less accurate – and less expensive – solar tracking systems designed for use with non-concentrating PV modules. The dimensions and weight of the MEPV modules are similar to conventional silicon PV modules, and thus standard PV system installation procedures are applicable. A description of these procedures and their associated costs can be found in a recent NREL report [2]. Capital and operating costs for two-axis solar trackers were taken from a recent article in an industry publication [7].

IV. Results and Discussion

The component cost models described above were employed in an analysis to determine the key drivers of MEPV cost, the expected costs of the initial MEPV design, and the cost implications of future designs.

A. Estimated Costs for the Initial MEPV Design

Estimation of MEPV system costs must begin with the selection of concentration ratio and cell size, which influence cell, optics, and module costs. Increased concentration ratio reduces cell costs, but increases the required thickness of the optics and thus the optical materials costs. Larger cell sizes also increase optics thickness and materials costs. Figure 3 summarizes the overall relationship between module cost and these two parameters. While higher concentration ratios appear to be attractive, the ability to maintain alignment of the optics given expected manufacturing tolerances will constrain the maximum practical concentration ratios to between 100X and 400X. Similarly, alignment tolerances and limitations of the module assembly and cell fabrication processes constrain the minimum cell size.

The total module costs represented in Figure 3 do not include the cost of cell placement. It was found that smaller cell sizes which minimized optics costs resulted in high pick-and-place costs; parallel cell placement technologies which have the potential to lower these costs and reduce or eliminate their dependence on cell size are currently under development.

B. Opportunities for Future Cost Reductions

The initial MEPV design considered above serves as a proof of concept, and should not be considered the lowest-cost design option. Utilization of the cost model has revealed opportunities for cost reduction in several of the module components. Major drivers of MEPV module cost are the lens materials, cell fabrication, and cell placement (pick and place). It is interesting to note that the cost of silicon is essentially negligible, due to the use of concentrating optics and the re-use of silicon wafers to produce extremely thin cells. Total silicon use is expected to be less than 2.2 g/W_p for one sun applications and 22 mg/W_p for 100X concentrators in MEPV modules, corresponding to silicon wafer costs of approximately \$0.05/W_p and \$0.005/W_p, respectively. Ongoing work is focused on future design and manufacturing concepts that will reduce materials costs in the optics systems, lower cell placement costs through the use of parallel placement techniques, and leverage less expensive cell fabrication equipment and methods.

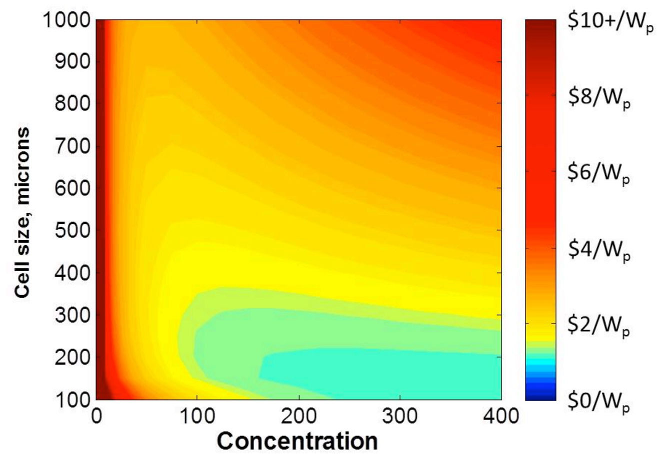

Fig. 3. Contour plot of module costs (\$/W_p) as a function of cell size and concentration ratio.

Although design of the MEPV module has little direct impact on costs of the BOS components and system installation (possible reduction in inverter costs due to the use of integrated electronics is an exception, but will not be addressed here), these costs can be reduced on a per-Watt basis by pursuing increases in cell efficiency which yield higher energy generation (see Figure 4); the use of multi-junction PV cells is a potential avenue for achieving such increases. As noted above, the MEPV modules are installed using standard PV BOS components and installation procedures, and thus MEPV is also able to benefit from any future cost reductions associated with these components; here we adopt NREL's projected 2020 materials and installation costs [2]. Figure 5 highlights the impact of higher module efficiency on the projected 2020 costs of the module (excluding PV cells), BOS, and system installation. The results clearly indicate a potential path to achieving the \$1/W_p price target set by DOE. It is also clear that the use of higher efficiency multi-junction PV cells will likely be necessary in order to reach this target. Based on projected 2020 module and

BOS costs, a PV cell that delivers 40% module efficiency would reduce total system cost (excluding PV cells) by 58% versus a system with 15% module efficiency. However, efforts to enhance cell efficiency to reduce BOS costs must balance the increased costs associated with the fabrication of high-efficiency cells; future cost analyses will establish MEPV cell efficiency targets in the context of this trade-off.

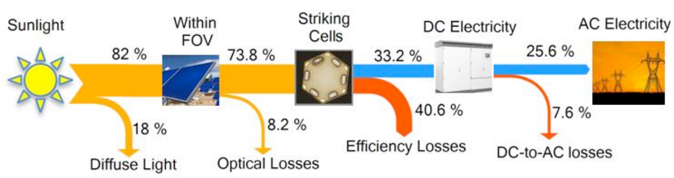

Fig 4. Energy flow diagram depicting losses accompanying the conversion of sunlight to AC electricity via MEPV systems. Module efficiency is assumed to be 40%.

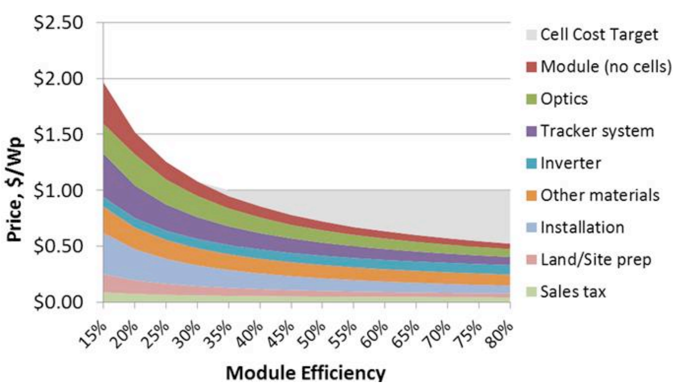

Fig. 5. Effect of increasing module efficiency on MEPV module, BOS, and installation costs for the initial module design. System BOS prices are 2020 estimates based on Ref [2]. Module costs do not include cell fabrication.

V. Conclusions and Future Research

A framework for analyzing the costs of a novel PV technology (MEPV) has been constructed, comprising modular cost models for the system components and installation. These models were employed to guide system design, identify major cost drivers, and estimate the overall cost of MEPV modules as well as the total installed system. The MEPV cost modeling results also offer insight into promising areas for future research and development. Based on these findings, efforts are underway to reduce costs in the optics system as well as the techniques for cell fabrication and placement. In addition, cost analysis has quantified the impact of employing multi-junction cells to achieve higher module efficiency; future work will explore the trade-offs between increasing cell efficiency and higher cell fabrication costs.

References

[1] US Department of Energy, “SunShot Vision Study,” February 2012.
[2] A. Goodrich, T. James, M. Woodhouse, “Residential, commercial, and utility-scale photovoltaic (PV) system prices in the United States: Current drivers and cost-reduction opportunities,” NREL Report No. TP-6A20-53347, 2012.
[3] T. James, A. Goodrich, A. Dobos, A. Lopez, M. Woodhouse, “Installed system cost targets for high concentration photovoltaic (HCPV) power systems,” presented at University of California Santa Barbara Technology Roundtable: Focus on Concentrator Photovoltaics, July 25, 2012.
[4] G. N. Nielson, M. Okandan, P. Resnick, J. Cruz-Campa, T. Pluym, P. Clews, E. Steenbergen, V. Gupta, “Microscale c-Si (C) PV cells for low-cost power,” *in 34th IEEE PVSC*, 2009, pp. 1816-1821.
[5] S. Bäumer and J. Mäkinen, “Cost modeling of injection-molded plastic optics,” in *Handbook of Plastic Optics*, 2nd Ed. Wiley-VCH, 2011.
[6] A. Goodrich, P. Hacke, Q. Wang, B. Sopori, R. Margolis, T. James, M. Woodhouse, “A wafer-based monocrystalline silicon photovoltaics road map: utilizing known technology improvement opportunities for further reductions in manufacturing costs,” *Solar Energy Materials and Solar Cells*, vol 114, 2013, pp. 110-135.
[7] PV News, “Mounting structures: A comparison of fixed and tracking applications with yield, cost, and market projections,” vol. 30, no. 7, p. 3, July 2011, Greentech Media, Inc.