A New Model to Determine Installed System Cost and LCOE for ARPA-E's MOSAIC Micro-Concentrator PV Program

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Ran Fu and Kelsey A.W. Horowitz
National Renewable Energy Laboratory

Daniel W. Cunningham and James Zahler
Advanced Research Projects Agency

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A New Model to Determine Installed System Cost and LCOE for ARPA-E's MOSAIC Micro-Concentrator PV Program

[1]Ran Fu, [1]Kelsey A.W. Horowitz, [2]Daniel W. Cunningham, [2]James Zahler

[1]National Renewable Energy Laboratory (NREL), Golden, CO 80401, United States

[2]Advanced Research Projects Agency – Energy (ARPA-E), Washington, D.C. 20585, United States

ABSTRACT — **The U.S. Department of Energy's Advanced Research Projects Agency - Energy (ARPA-E) started a 3-year program in December 2015 called Microscale Optimized Solar-cell Arrays with Integrated Concentration (MOSAIC) that consists of 11 teams from various locations across the United States. The goal of MOSAIC is to leverage attributes of conventional flat-plate photovoltaic (PV) system configuration and concentrator photovoltaic (CPV) module technology to produce a new class of modules for residential, commercial, and utility-scale markets. The intent is to increase performance and facilitate cost-effective deployment of solar power systems across a wide range of geographical locations in part by concentrating the direct components of the sun's irradiance and also collecting diffuse irradiance. This paper describes a collaborative effort between ARPA-E and the National Renewable Energy Laboratory (NREL) to develop a bottom-up system cost model for MOSAIC research teams. The model includes an estimate of regional, all-in CPV installed cost and levelized cost of energy (LCOE) by using customized input parameters, such as module efficiency, cost, and physical dimensions. This techno-economic cost model can help researchers analyze tradeoffs among different design parameters and then prioritize their distinct research opportunities. Moreover, it establishes a standardized cost benchmark methodology for MOSAIC micro-CPV systems and allows for normalized comparison against traditional CPV and today's highly competitive, flat-plate PV systems. The model is a valuable design tool within the program, helping to validate the various technical approaches and compare future deployed system competitiveness versus incumbent technologies in the PV industry.**

Index Terms — **Concentrator photovoltaic (CPV), balance of system (BOS), bottom-up cost model, levelized cost of energy (LCOE), solar energy, MOSAIC.**

I. INTRODUCTION

Currently, three types of solar power systems exist commercially: solar photovoltaic (PV), concentrated solar power (CSP), and concentrator photovoltaic (CPV). Solar PV, which is the most widely deployed type of solar system, offers a clean, renewable source of electricity at a cost level that has been increasingly competitive. Although it has experienced dramatic growth and cost reductions in recent years, solar PV represents only 1% of U.S. power generation [1]. While today's single-junction, flat-plate modules are making impressive progress, new technologies that achieve higher efficiency and/or lower cost could potentially propel the growth of solar even faster. One way to increase the efficiency of solar PV systems is by using CPV modules, which use optical devices to concentrate sunlight onto a smaller, high efficiency solar PV receiver. This method allows the system to generate more power with a much smaller footprint. However, CPV only converts direct sunlight, not diffuse solar radiation (sunlight scattered by the atmosphere and clouds); therefore, CPV is only viable in a limited geographic range, namely the southwestern United States where direct sunlight predominates. CPV has not been widely adopted because of rapidly declining flat-plate prices, the added material cost of the receiver and solar tracking systems, more limited field experience with these systems [2][3] and the surplus overall solar market when CPV was introduced in the field. Led by the Advanced Research Projects Agency – Energy (ARPA-E), the Microscale Optimized Solar-cell Arrays with Integrated Concentration (MOSAIC) program seeks to overcome these challenges and develop arrays of very small CPV systems (known as microscale CPV technology) that integrate more affordable materials and manufacturing techniques. In addition, MOSAIC seeks solutions that will utilize diffuse sunlight as well as direct sunlight in order to expand the geographic regions in which the benefits of CPV may be exploited cost-effectively [2].

In the MOSAIC program, project teams hope to develop microscale CPV systems that are similar in cost and size to conventional flat-plate solar PV systems but with greatly increased performance levels. To accomplish this goal, MOSAIC's multidisciplinary teams will leverage existing experience and expertise from conventional flat-plate PV, CPV, manufacturing, optical engineering, and material science to produce a new class of PV panels without increasing manufacturing costs. By designing CPV solutions for use in all three primary market sectors (residential, commercial, and utility-scale) and across a wide range of solar resources, the new PV technology will facilitate cost-effective deployment of solar power systems across a wide range of geographical locations, providing consumers with more opportunities to choose their own source of power generation and potentially reducing consumer electricity costs.

Past National Renewable Energy Laboratory (NREL) studies employed in-house bottom-up cost models to estimate PV system costs [4][5]. Some prior studies have also published data or top-down estimates of total installed system costs and/or the levelized cost of energy (LCOE) associated with different CPV designs [3][6]. Paap et al. provide qualitative discussion on how acceptance angle could influence system cost [6], but a bottom-up cost model allowing for quantitative evaluation of system cost drivers for dual-axis trackers with CPV has not previously been published. This paper introduces a bottom-up cost model of a dual-axis tracked ground-mounted system developed by NREL and incorporates our existing models of system costs for fixed-tilt and single-axis tracking systems as a function of efficiency and location. Further, all those cost models are integrated in the MOSAIC model. A simple LCOE calculator is also included. The resulting, integrated MOSAIC model is being used to support techno-economic analysis for MOSAIC awardees for their CPV applications (residential, fixed-tilt, single-axis tracker or dual-axis tracker). In Section II, we describe the cost model structure. In Section III, we review the LCOE results from the MOSAIC model. Finally, in Section IV, we present results using the model for two example systems: a fixed-tilt, residential rooftop system with internal tracking and a ground-mounted, utility-scale system with traditional dual-axis tracking. Throughout this report, we discuss how the model and results can be used to guide MOSAIC program research.

II. SYSTEM COST MODEL FOR MOSAIC

Our MOSAIC cost model includes installed costs for four different system types: fixed-tilt, residential rooftop systems; fixed-tilt, utility-scale ground-mounted systems; utility-scale, ground-mounted single-axis tracked systems; and utility-scale, ground-mounted dual-axis tracked systems. For the fixed-tilt and single-axis tracked cases, we assume that the total non-module costs are the same as associated traditional, flat-plate PV systems because the MOSAIC program targets BOS system designs with similar form factors to incumbent technology. Data from [4] on non-module costs as a function of efficiency and location (state level) are used for these systems in our model. In this paper, the key model functions, such as LCOE calculation and module efficiency impact on system costs are presented.

The dual-axis tracked system cost assumes a dual-axis tracker with a traditional pedestal architecture consisting of a column, tubing, racking, brackets, gear drive for dual-axis tracking, foundation, and a tracker control unit. The functional flow of the model is illustrated in Fig. 1. Users can plug in model inputs, including module characteristics (such as price, weight, dimensions, efficiency, and degradation rate), system configurations (such as acceptance angle, tracker area, first-year energy yield, system life, and operation and maintenance [O&M] costs), location (state level), and financial parameters (capital structure). In this case, efficiency is defined as the rated direct current (DC) module efficiency at Concentrator Standard Test Conditions (CSTC); however, alternative standards for rating efficiency, still under development [2], may eventually be more applicable to MOSAIC-type module designs. Intermediate values, such as wind speed and snow loading, are calculated based on these inputs to further determine engineering design factors including foundation depth, racking component quantity, and dual-axis tracking gear drive capacity. Subsequently, cost factors related to engineering design factors, such as foundation cost, racking cost, labor installation cost, and gear drive cost, are computed. The final outputs include total system cost categories and are grouped into module, tracker, structural balance of systems (BOS), electrical BOS, permitting, and interconnection as well as overhead for Engineering Procurement Construction (EPC) firms and the developer.

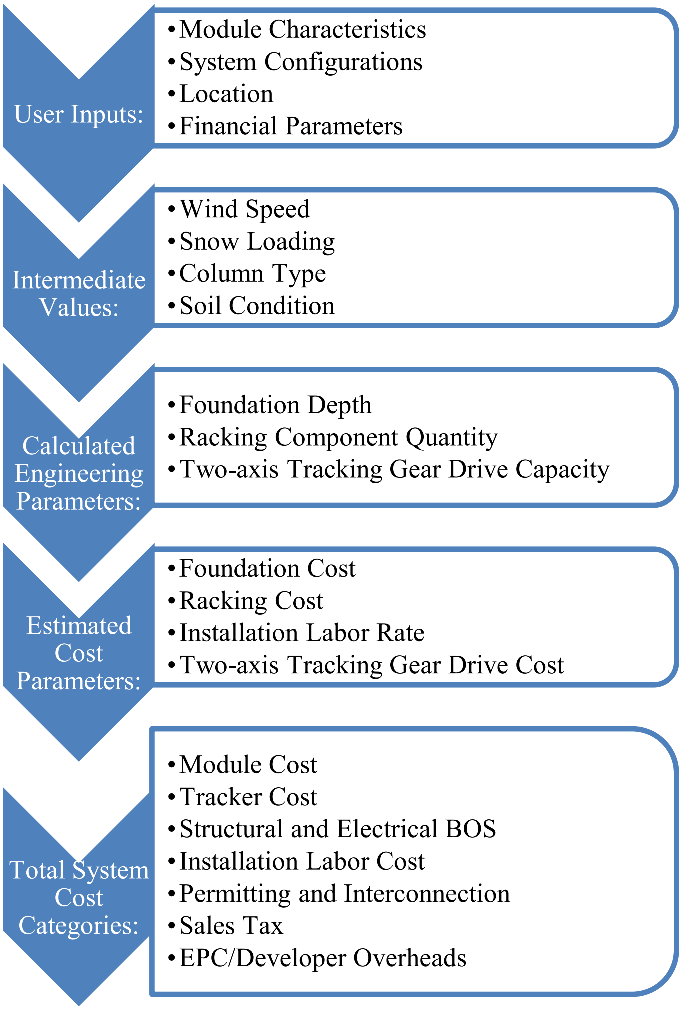

Fig.1. Model Process Flow

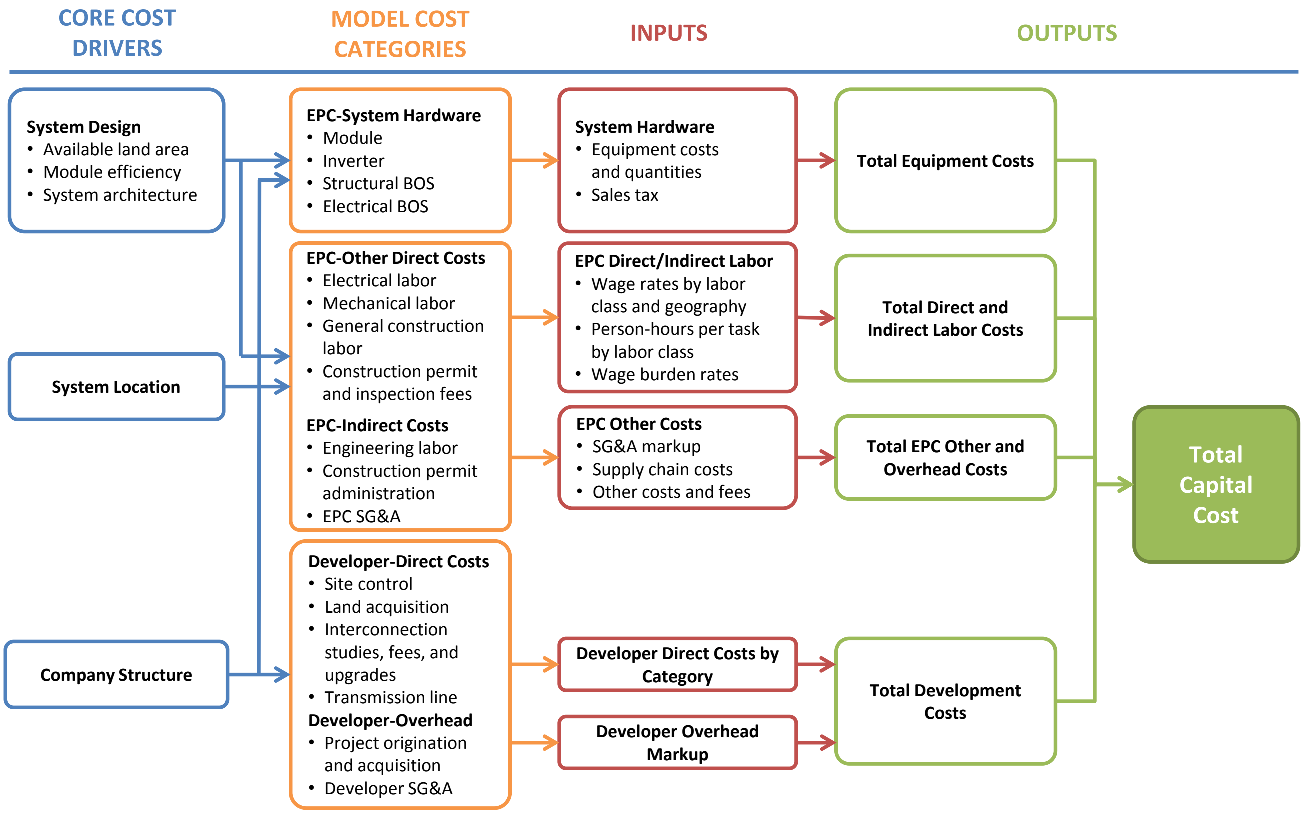

Fig. 2. Structure of the bottom-up cost model

A detailed bottom-up cost structure of our model is presented in Fig. 2. Overall, total CPV system upfront capital costs are broken into EPC costs and developer costs. An experienced EPC is typically hired by a developer for construction tasks. EPC soft costs are driven by region-specific structural design criteria, such as wind speeds and snow loading; thus, the resulting differences in installed costs can vary significantly across the country. To incorporate these cost drivers, a structural design tool based on the American Society of Civil Engineers (ASCE) design code [7] and a construction cost estimating model are used to determine the EPC hardware costs (including racking, mounting, and foundation) and related EPC soft costs (including related labor and equipment hours required in any given U.S. location).

Developers typically use an internal rate of return (IRR) target or a specific power purchase agreement (PPA) to determine the project's net present value (NPV). Thus, the value of a CPV system, in terms of NPV, is dependent on different corporate strategies, such as capital structures, market competition, and local electricity rates. In this paper, a "cost approach" is used for CPV system installed cost ($/W), and an "income approach" is used for CPV system LCOE [4]. Key model inputs and assumptions are summarized in Table I.

TABLE I

UTILITY-SCALE CPV SYSTEM MODEL INPUTS AND ASSUMPTIONS IN 2016 [4]

Model components:	*Model inputs:*
Module	User input (for incumbent technologies, commodity average selling prices [ASPs] are used)
Inverter	$0.15/W, residential, fixed-tilt (rooftop) $0.09/W, utility-scale, fixed-tilt (ground-mount) $0.10/W, utility-scale, single-axis (ground-mount) $0.11/W, utility-scale, dual-axis tracker for CPV Note: Inverter prices are the same in $/Wac but different in $/Wdc when as DC-to-AC ratios vary.
Racking and foundation	Determined by wind speed, snow loading, and material cost index by state
Balance of system	Determined by the size of the CPV system
Installation labor	Non-union at rates taken from BLS statistics survey average by state
Sales tax (if any)	Determined by location (state level)
EPC overhead and profit	<10 MW, use 10%; >100 MW, use 8% 10~100 MW, use linear interpolation
Transmission line (gen-tie line)	<10 MW, use 0 mile; >200 MW, use 5 miles 10~200 MW, use linear interpolation
Land acquisition	$0.03/W
Interconnection	$0.03/W
Permitting (if any)	$500,000 for California; $250,000 for other states
Contingency	4%
Developer overhead	<10 MW, use 15%; >100 MW, use 10%; 10~100 MW, use linear interpolation

III. LCOE MODEL

Although LCOE ($/kWh) cannot capture all power systems or societal costs and benefits, it still provides a transparent metric for understanding costs and differences among technologies. Our MOSAIC cost model links results from the bottom-up system cost model to an LCOE calculator described by Eq. 1. This LCOE calculation involves simplified financial and performance modeling compared with NREL's System Advisory Model (SAM) or other tools used for planning specific installations or projects. This allows researchers to quickly and easily compare their designs to incumbent module types on an "apples-to-apples" technology basis without having to develop their own sets of financial assumptions, learn more complex tools, or, in general, deal with models that include detail beyond what is required at their stage of development and whose use could result in analysis errors.

$$LCOE = \frac{C_{upfront} + \sum_{n=0}^{N} \frac{O\&M_n}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_1(1-r)^n}{(1+d)^n}} \qquad \text{(Eq. 1)}$$

where:

- $C_{upfront}$ is the total upfront capital cost in $\$/W_{p(DC)}$
- n is the year index and N is the project life
- E_1 is the first-year energy yield, in $kWh/kW_{p(DC)}$
- $O\&M_n$ is the total O&M expenses incurred in year n, in $\$/W_{p(DC)}$
- r is the degradation rate
- d is the discount rate, which we set equal to the weighted-average cost of capital (WACC).

The first-year energy yield is a key parameter to Eq. 1. This value is calculated by the MOSAIC teams and input into the LCOE model. This energy yield could be increased, by, for example, increasing the acceptance angle of the module in order to collect more diffuse light. Spectral effects and temperature effects must be carefully considered in the calculation of first-year energy yield. While typical multi-junction solar cells used in CPV designs have a lower temperature coefficient than c-Si cells, the temperature response of optics required for concentration and tracking (if internally tracked) for MOSAIC systems must be considered. Some optical systems can be quite sensitive to temperature and/or humidity. In addition, spectral effects at both the cell and module level on energy yield must also be considered. Alignment issues, which may also be coupled with temperature or spectrally dependent effects as well as soiling (which causes proportionally higher losses in concentrated component) should also be considered.

The input assumptions used in the LCOE calculator are shown in Table II. These are based on data for traditional flat-plate systems defined in 2016 [4]. The DC-to-AC ratio for dual-axis tracking is assumed to be the same as the single-axis tracking case; we were not able to obtain data on the DC-to-AC ratio typically used for CPV systems today.

TABLE II

DEFAULT INPUT ASSUMPTIONS USED IN THE LCOE MODEL [4]

Parameter:	*Value:*
Percent financing from debt	80%
Cost of debt	6.9%
Cost of equity	23.1%
Effective corporate tax rate	41.5%
WACC (calculated using the above)	7.84%
Federal investment tax credit (ITC) level	30%
State and local incentives or tax credits	None
DC-to-AC ratio	1.15 for residential rooftop, 1.2 for utility-scale single-axis tracked, 1.4 for utility-scale ground-mounted fixed-tilt, 1.2 for dual-axis tracked
Project life	30 years
Inverter lifetime	10 years
Inverter replacement cost	$0.15/W for residential rooftop, $0.10/W for utility-scale single-axis tracked, $0.09/W for utility-scale ground-mounted fixed-tilt, $0.11/W for dual-axis tracked

With the model options, we include the ability to compare LCOE for MOSAIC designs to current performance and cost for two incumbent technologies—monocrystalline silicon (c-Si) and cadmium telluride (CdTe)—in three locations—Phoenix, Arizona (high DNI), Kansas City, Missouri (medium DNI), and New York, New York (low DNI). First-year energy yield values for c-Si and CdTe in each of these locations were calculated offline using SAM and input to the MOSAIC LCOE model in the form of a look-up table.

IV. MODEL RESULTS

The MOSAIC cost model may be applied to a range of analyses useful for setting research targets and evaluating the potential of different designs, including assessment of cost-performance tradeoffs, sensitivity analysis, and LCOE comparison of a module design to incumbent technology. In this section, we provide examples of fixed-tilt, residential rooftop systems and ground-mount, dual-axis tracked systems.

A. Fixed-Tilt, Residential Rooftop Systems

CPV designs that incorporate internal tracking mechanisms do not require external tracking. Some MOSAIC projects are developing internally tracked modules with similar form factors as traditional flat-plate modules. These designs would incur the same installation costs as traditional flat-plate systems. The factors differentiating the LCOE from incumbent technology are efficiency, energy yield, module price, O&M costs, and module degradation rate. The MOSAIC cost model can be used to conduct simple parametric analysis of how these variables influence LCOE; this analysis is useful for a variety of purposes, including setting technical targets for specific projects. For example, say a project team has modeled energy yield (energy produced per rated power of the module) and estimated O&M costs and degradation, and wants to know what module efficiencies and prices to target with their design. This team could calculate the dependence of LCOE on both efficiency and module price, as shown in Figure 3. Efficiency drives reductions in LCOE by decreasing non-module system costs in dollars per watt. Efficiency also reduces the cost of the module in dollars per watt, although the total module cost may be constant or increase depending on if and how area-related module costs were changed in order to achieve increased efficiency; in Figure 3, we vary both module efficiency and module price independently. For this illustrative example, we assume a first-year energy yield of 2,100 kWh/kW$_{p(DC)}$ in Phoenix, Arizona. Using SAM, we calculate the first-year energy yield for a residential rooftop system with traditional monocrystalline silicon (c-Si) panels to be 1,800 kWh/kW$_{p(DC)}$; for a utility-scale, ground-mount single-axis tracked system using c-Si panels in Phoenix, we calculate a first-year energy yield of 2,459 kWh/kW$_{p(DC)}$. Our input assumption lies in the middle of these values and represents a number that cannot be achieved with existing fixed-tilt, flat-plate designs but may be feasible if concentration and an internal tracking mechanism are used. Note that this does not correspond to an energy yield value computed for a particular MOSAIC design, and an understanding of the energy yield for designs in the MOSAIC portfolio is still being developed for each approach within the program. MOSAIC designs may have energy yields above or below this value.

As can be seen from Figure 3, LCOE savings from efficiency are non-linear and start to asymptote as efficiency increases. The curve of efficiency versus LCOE will evolve over time according to how area-dependent, capacity-dependent (rated power), and fixed non-module system costs evolve. Also, our previous Q1 2016 US Solar PV Benchmark [4] demonstrates the US LCOE maps by using the similar financial parameters but conventional flat-plate crystalline silicon PV system configurations.

The results shown in Figure 3 depend on the input values for first-year energy yield, degradation rate, O&M costs, and system life, in addition to financial assumptions. Figure 4 shows the sensitivity of LCOE to these input parameters. The base case—an arbitrarily chosen base case which could correspond to a set of possible values associated with an ultra-high efficiency module—assumes a $0.50/W$_{p(DC)}$ module price and 30% module efficiency. MOSAIC teams can use the model to run sensitivity analysis for their specific set of base case assumptions.

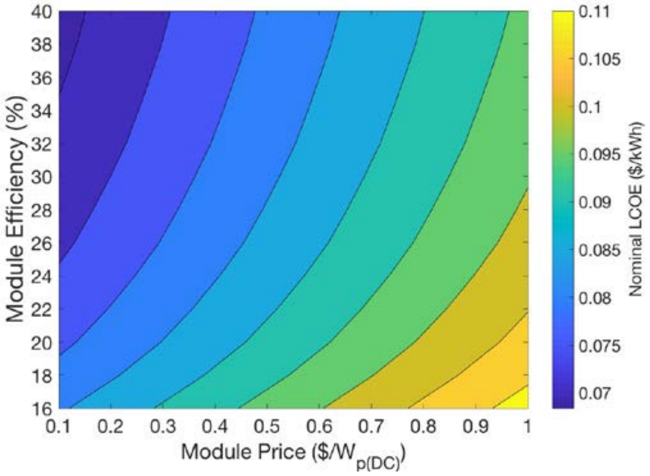

Fig. 3. LCOE versus module cost and efficiency for a fixed-tilt, residential rooftop system in Phoenix, Arizona, assuming a first-year energy yield of 2,100 kWh/kW$_{p(DC)}$, 0.5% degradation rate, 30-year system life, and O&M cost of $20/kW$_{p(DC)}$/year, including a federal ITC at 30%.

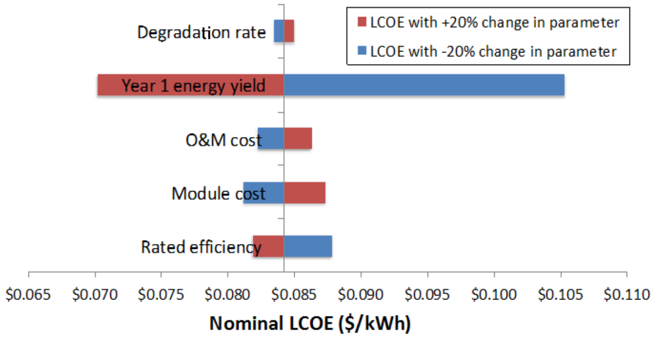

Fig. 4. Sensitivity of LCOE to ±20% changes in key input parameters for fixed-tilt residential rooftop systems. Base case corresponds to a $0.50/W$_{p(DC)}$ module price and 30% module efficiency, including a federal ITC at 30%.

B. Ground-Mount, Dual-Axis Tracked Systems

Our bottom-up cost model for a dual-axis CPV tracker shows that one key driver of tracker cost is total loading on the array. This is determined by the dimensions of the array on the pedestal as well as the wind and snow loading in a particular location. Increasing the array dimensions increases the loading. Adding additional modules to the array increases the watts per array, the denominator of cost per watt, but this decrease is moderated by increases in costs associated with high loading on larger area arrays. Additionally, the total number of modules on the array affects installed cost because additional labor time and BOS materials are required to install a larger number of modules. For a given module size, there is an optimum number of modules per array that balances these tradeoffs. The optimal number of modules per array can be estimated using the MOSAIC cost model and the optimal point used for further analysis of the LCOE for a given module design.

Figure 5 compares the sensitivity of non-module total system costs to module efficiency for dual-axis tracked and single-axis tracked system types. Module efficiency improvements have reduced the number of modules required to construct a system of a given size, thus reducing hardware costs as well as soft costs from direct labor and related installation overhead. This figure shows that the cost savings from high module efficiency is more significant for the dual-axis tracker than for the single-axis tracker. This result is caused by higher construction cost per column for dual-axis trackers than for single-axis trackers. Thus, high module efficiency will be more impactful on the dual-axis CPV systems than the single-axis flat-plane systems.

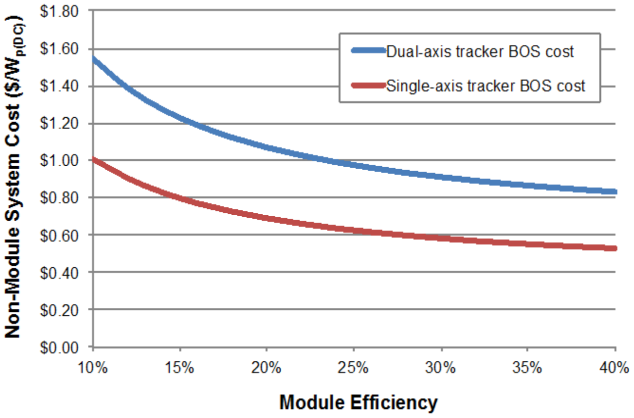

Fig. 5. Non-module system costs versus module efficiency for dual-axis versus single-axis tracked systems

A key question for the MOSAIC program is the value of reducing the required tracking accuracy for a dual-axis tracker, particularly compared to traditional high concentration PV (HCPV) designs. As discussed in Section III, larger acceptance angles allow for the collection of some diffuse light and, in some cases, additional circumsolar radiation, increasing energy yield and all else equal reducing LCOE. Depending on the location, diffuse light and circumsolar radiation are typically around 10% and 1% to 10% (higher in very hazy locations) of the total irradiance, respectively. The gains associated with increased diffuse light harvesting can be significant if a lower concentration ratios are used, for example by using low concentration onto a silicon bottom cell and higher concentration onto a III-V top cell. These energy yield benefits are calculated by the MOSAIC teams for their specific designs and then input to the MOSAIC cost model to determine the associated LCOE savings. Another potential benefit of increased acceptance angle, which can be estimated using the bottom-up, dual-axis tracker cost model developed here, is reduced tracker costs associated with the relaxation of tracking accuracy requirements. The required tracking accuracy depends on the acceptance angle of the module (the half angle) in addition to any accuracy losses resulting from misalignment. Our interviews with tracker companies and members of the CPV industry, along with our own primary analysis, indicate that for tracking accuracies ≥0.5°, the structure is typically designed to withstand wind and snow loading in non-operating (stowed) conditions, and thus, the cost of the tracker is not reduced by further relaxations of the required tracking accuracy. For tracking accuracies between 0.2°–0.3° and 0.5°, you may be required to use a higher accuracy slew drive, increasing costs. For even smaller tracking accuracy requirements (≤0.2°–0.3°), the structural components of the tracker may also need to be reinforced to meet deformation criteria, increasing structural BOS costs. In the latter case, the additional required material is dependent on the specific tracker and module design and requires detailed simulation, such as finite element analysis, to compute. These calculations are beyond the scope of this work but should be considered for designs anticipated to have tight tracking accuracy requirements. Other possible benefits to larger acceptance angles include greater tolerance to gross misalignment due to installation or operational error of the trackers.

V. SUMMARY

A new bottom-up cost model developed by NREL and ARPA-E can be used for MOSAIC research teams to conduct consistent techno-economic analysis, including CPV installed cost and LCOE. For instance, tradeoffs between module cost and performance—including rated efficiency, energy yield, degradation, and acceptance angle—can be rapidly evaluated to guide research directions. This model is a valuable design tool within the program, helping to validate the various technical approaches and compare future deployed system competitiveness versus incumbent technologies in the PV industry on an apples-to-apples, technology basis.

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