An Analysis of Techno-Economic Requirements for MOSAIC CPV Systems to Achieve Cost Competitiveness

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Incumbent Flat Plate PV Technology

- Flat-plate c-Si is > 90% of the PV market
- Module costs and prices have decreased rapidly and significantly
  - $0.35/W ex-factory gate average price in 2017
- Single-junction devices have limits on efficiency
- Fixed-tilt systems suffer from cosine losses
CPV Concepts and the MOSAIC Program

Traditional HCPV Systems

- Myriad of different designs
- Thicker than traditional flat plate modules
- Require accurate 2-axis tracking
- Cannot collect diffuse sunlight

Micro-scale Optimized Solar cell Arrays with Integrated Concentration (MOSAIC)

- Myriad of different designs
- Form factor similar to flat plate technology: Approx. 2.5cm array height
- Either have relaxed tracking requirements or do not require external tracking
- Most able to collect some diffuse light
Techno-Economic Analysis Overview

• Conducted bottom-up cost analysis relevant to a range of MOSAIC designs, including fixed-tilt and tracked systems
  o Built a new bottom-up, engineering cost model of a dual-axis tracker for modeling tracked MOSAIC designs
  o Leveraged NREL’s existing bottom-up system models of fixed-tilt rooftop and ground mount systems
  o Based on 2016 system costs
• Created a simplified LCOE calculator to use for “apples-to-apples”, technology-based comparisons
• Applied this modeling to:
  o Evaluate and validate program goals
  o Compare & contrast different module design aspects
  o Set cost and performance targets for specific module types in residential, commercial, and utility-scale markets
  o Assess different aspects of MOSAIC awardees designs and their potential competitiveness against incumbent technology
Harvest Efficiency

Currently, HCPV systems are rated using only direct normal irradiance (DNI) according to the IEC 62670-1 standard.

MOSAIC efficiency metric is harvest efficiency, which is based on total input irradiance.

$$\eta_{\text{Harvest},DC} = f_{\text{DNI}} \cdot g(\theta, \phi)_{\text{DNI}} \cdot \eta_{\text{opt},\text{DNI}} \cdot \eta_{\text{PV, DNI}} \cdot F_{\text{DNI}} + (1 - f_{\text{DNI}}) \cdot g(\theta, \phi)_{\text{DIFF}} \cdot \eta_{\text{opt,DIFF}} \cdot \eta_{\text{PV,DIFF}} \cdot F_{\text{DIFF}}$$
### Potential Competitiveness of Internally-Tracking MOSAIC Systems in Different Markets

**Advantage of MOSAIC systems:** ability to reach higher efficiencies and potentially have higher energy yields

- Final energy yield that will be realized by MOSAIC systems is currently uncertain

**Residential rooftop systems** have higher balance-of-system (BOS) costs, and so the advantage of higher efficiency is greater than for utility-scale.

- Advantage of MOSAIC systems will depend on the BOS cost structure at the time of commercialization

**Theoretical MOSAIC System Aligns with MOSAIC Targets:**

- **Harvest efficiency:** \( \geq 30\% \) (30% of total insolation)
- **Module production cost:** $0.41/W - $0.58/W ($0.50/W)
- **Degradation rate:** \(<1\%/year\) (1%/year)

<table>
<thead>
<tr>
<th>System Type</th>
<th>Nominal LCOE (cents/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono c-Si Residential Rooftop</td>
<td>10</td>
</tr>
<tr>
<td>Theoretical MOSAIC</td>
<td>8</td>
</tr>
<tr>
<td>Mono c-Si Utility-Scale Fixed-Tilt Ground-Mount</td>
<td>5</td>
</tr>
<tr>
<td>Theoretical MOSAIC</td>
<td>4</td>
</tr>
</tbody>
</table>

Error bars on MOSAIC represent some possible high and low energy yield scenarios.
Effects of Module Efficiency and Price

- LCOE competitiveness depends on many factors
- Two primary drivers are module efficiency and price
- The potential for increased energy density associated with MOSAIC systems can provide additional value in space-constrained applications

Assumptions
- Phoenix, AZ
- Same degradation as mean value for c-Si (0.5%/year)
- 2,100 kWh/kW (compared to 1,800 kWh/kW for mono c-Si)

Mono c-Si LCOE for comparison
Modeled Two-Axis Tracker Costs in Phoenix, AZ

- Trackers with accuracies less than 0.5° are designed for stow conditions → little cost change
- For accuracies better than 0.3°, you may require additional structural reinforcement, incurring additional costs, specific to each module/system design
- Trade-offs for increasing tracker area
  - Wind and snow loading increases, driving up cost per tracker to maintain accuracy (higher increase with more stringent tracking requirements)
  - Watts per tracker increases, driving down overall installed cost per watt

Curve varies depending on dimensions of tracker array, the size of the modules, and the location of installation
Two-Axis MOSAIC versus Single-Axis Flat Plate System at Utility-Scale

- 80% of utility-scale installations in the US in 2016 used 1-axis tracking
- Higher energy yield requirements for MOSAIC because of increased cost associated with the dual-axis tracker, even with relaxed accuracy requirements
  - 2-axis trackers are earlier in the learning curve than 1-axis trackers

**Comparison of System Characteristics to Achieve 5.2¢/kWh in Kansas City, MO**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Module Efficiency</th>
<th>Module Price</th>
<th>Total Installed System Price</th>
<th>Degradation rate</th>
<th>Energy Yield to hit 5.2¢/kWh LCOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current CdTe, 1-axis tracking</td>
<td>16%</td>
<td>$0.39/W_p</td>
<td>$1.20/W</td>
<td>0.4%/year</td>
<td>1,966 kWh/kW_p (modeled energy yield for CdTe system)</td>
</tr>
<tr>
<td>Theoretical MOSAIC, 2-axis tracking: meets program targets</td>
<td>30%</td>
<td>$0.50/W_p</td>
<td>$1.46/W</td>
<td>1%/year</td>
<td>2,438 kWh/kW_p (required to hit 5.2¢/kWh)</td>
</tr>
<tr>
<td>Theoretical MOSAIC, 2-axis tracking: exceeds program targets</td>
<td>40%</td>
<td>$0.20/W_p</td>
<td>$1.04/W</td>
<td>0.4%/year</td>
<td>1,829 kWh/kW_p (required to hit 5.2¢/kWh)</td>
</tr>
</tbody>
</table>
Planar micro-tracking LCOE modeling at Penn State

Technology Summary

- Fixed-tilt CPV panels, 300x concentration
- μ-scale 3J solar cells, ~42% efficient
- panel efficiency 35% of DNI

Annual energy generation

- Based on PV Watts TMY data & NREL SPA
- Comparison with 19% Si panel
- Metric: annual kWh/kWp(dc)

<table>
<thead>
<tr>
<th></th>
<th>19% Si</th>
<th>35% CPV</th>
</tr>
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<tbody>
<tr>
<td>AZ</td>
<td>1830</td>
<td>1610</td>
</tr>
<tr>
<td>MO</td>
<td>1450</td>
<td>1160</td>
</tr>
<tr>
<td>NY</td>
<td>1350</td>
<td>1070</td>
</tr>
</tbody>
</table>

Residential LCOE & installation cost comparison

<table>
<thead>
<tr>
<th></th>
<th>AZ</th>
<th>MO</th>
<th>NY</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCOE ($/kWh)</td>
<td>$0.063</td>
<td>$0.080</td>
<td>$0.089</td>
</tr>
<tr>
<td>Install ($/Wp)</td>
<td>$2.67</td>
<td>$2.66</td>
<td>$2.84</td>
</tr>
<tr>
<td>LCOE ($/kWh)</td>
<td>$0.073</td>
<td>$0.100</td>
<td>$0.113</td>
</tr>
<tr>
<td>Install ($/Wp)</td>
<td>$2.37</td>
<td>$2.33</td>
<td>$2.50</td>
</tr>
</tbody>
</table>

Conclusions

- CPV wins on install cost, Si wins on LCOE
- Key difference is 30 yr degradation rate
  - 0.4%/yr Si vs. 1%/yr CPV assumed

Analysis courtesy of Dr. N Giebink, Penn State University
Summary and Conclusions

- A bottom-up model created from NREL for MOSAIC is being used by awardees to assess their specific systems/designs.
- MOSAIC systems could become cost-competitive with other PV technology, particularly in space-constrained applications:
  - Residential and commercial BOS savings
  - We presented an example of this for a residential application and utility-scale application with Penn State’s design.
- However, this will depend on the specifics of the system, including:
  - Manufacturing cost per watt
  - Energy yield/harvest efficiency
  - System degradation
- Lower tracking accuracy requirements translate to lower tracker costs, to a point.
- The modeled premium for two-axis trackers means high performance is required for CPV systems to break-even with existing technology on single-axis trackers in utility-scale markets.
Thank you!

Questions?
Simplified LCOE equation

\[
LCOE = \frac{C_{\text{upfront}} + \sum_{n=0}^{N} \frac{O \& M_n}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_1(1-r)^n}{(1+d)^n}}
\]
II. System Cost Model for MOSAIC

- The dual-axis tracked system cost model assumes a traditional pedestal architecture
- Fixed-tilt and 1-axis tracking architectures identical to those currently used for flat-plate designs
- Users input their specific module characteristics and get out system price and LCOE
- Can compare LCOE to existing technology in 3 locations: Phoenix, Kansas City, New York
- Simplified LCOE model and default financial inputs for easy use by scientific researchers and early-stage projects

User Inputs
- Module Characteristics
- System Configurations
- Location
- Financial Parameters

Intermediate Values
- Wind Speed
- Snow Loading
- Column Type
- Soil Condition

Calculated Engineering Parameters
- Foundation Depth
- Racking Component Quantity
- Two-axis Tracking Gear Drive Capacity

Estimated Cost Parameters
- Foundation Cost
- Racking Cost
- Installation Labor Rate
- Two-axis Tracking Gear Drive Cost

Total System Cost Categories
- Module Cost
- Tracker Cost
- Structural and Electrical BOS
- Installation Labor Cost
- Permitting and Interconnection
- Sales Tax
- EPC/Developer Overheads
II. System Cost Model for MOSAIC

<table>
<thead>
<tr>
<th>CORE COST DRIVERS</th>
<th>MODEL COST CATEGORIES</th>
<th>INPUTS</th>
<th>OUTPUTS</th>
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</thead>
<tbody>
<tr>
<td>System Design</td>
<td>EPC-System Hardware</td>
<td>System Hardware</td>
<td>Total Equipment Costs</td>
</tr>
<tr>
<td></td>
<td>• Module</td>
<td>• Equipment costs and quantities</td>
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<tr>
<td></td>
<td>• Inverter</td>
<td>• Sales tax</td>
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<tr>
<td></td>
<td>• Structural BOS</td>
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<td></td>
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<tr>
<td></td>
<td>• Electrical BOS</td>
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<tr>
<td>System Location</td>
<td>EPC-Other Direct Costs</td>
<td>EPC Direct/Indirect Labor</td>
<td>Total Direct and Indirect Labor Costs</td>
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<tr>
<td></td>
<td>• Electrical labor</td>
<td>• Wage rates by labor class and geography</td>
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<tr>
<td></td>
<td>• Mechanical labor</td>
<td>• Person-hours per task by labor class</td>
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<tr>
<td></td>
<td>• General construction labor</td>
<td>• Wage burden rates</td>
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<tr>
<td></td>
<td>• Construction permit and inspection fees</td>
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<tr>
<td>Company Structure</td>
<td>EPC-Indirect Costs</td>
<td>EPC Other Costs</td>
<td>Total EPC Other and Overhead Costs</td>
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<tr>
<td></td>
<td>• Engineering labor</td>
<td>• SG&amp;A markup</td>
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<td></td>
<td>• Construction permit administration</td>
<td>• Supply chain costs</td>
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<tr>
<td></td>
<td>• EPC SG&amp;A</td>
<td>• Other costs and fees</td>
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<tr>
<td></td>
<td>Developer-Direct Costs</td>
<td>Developer Direct Costs by Category</td>
<td>Total Development Costs</td>
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<tr>
<td></td>
<td>• Site control</td>
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<td></td>
<td>• Land acquisition</td>
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<td>• Interconnection studies, fees, and upgrades</td>
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<td>• Transmission line</td>
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<td>Developer-Overhead</td>
<td>Developer Overhead Markup</td>
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<tr>
<td></td>
<td>• Project origination and acquisition</td>
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<td>• Developer SG&amp;A</td>
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