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*Published in:*
Solar Energy

*DOI:*
10.1016/j.solener.2021.01.051

Published: 01/03/2021

*Document Version*
Peer reviewed version

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Geographic Potential of Shotcrete Photovoltaic Racking: Direct and Low-concentration Cases
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Abstract:
Relentless cost declines in solar photovoltaic (PV) modules have radically reduced system costs, but the result is that racking costs have become more important. In this study a new open source racking method using earth and shotcrete-based ground mounts is investigated in two geographic regions: 1) Boa Vista, Brazil, where PV rows have an optimized shallow tilt angle and can be close-packed and 2) Kingston, Canada, where racks can make use of low concentration in the required inter-row spacing. Models are developed for both locations with single, double and triple vertical stacked shotcrete-based ground-mounted PV racking systems. Using these models bills of materials and energy simulations are produced to provide a cost benefit analysis specifically for the shotcrete racks. The results show that for utility-scale PV systems near the equator, a shotcrete racking system could reduce racking costs by 18% to 22% from the least expensive conventional racking and as much as 47% reduction for more expensive commercial racking. Economics is less clear for shotcrete-based racking at higher latitudes that incorporate low-concentration reflectors as they can be both lower and higher costs than conventional racking, but would be expected to produce at least 18% more electricity per installed Watt. Overall this novel racking concept was found to be promising, particularly for desert regions where it could reduce soiling losses. The results of this study indicate a need for future work to fully evaluate the potential of shotcrete racking to reduce solar electricity costs at the utility scale.

Keywords: photovoltaic; low concentration; ground mount; racking; utility solar; low concentration

1. Introduction

The solar photovoltaic (PV) industry is growing rapidly due to improved technology and substantial reduction in module costs (Feldman, et al., 2012; Barbose, 2020). It is predicted from International Renewable Energy Agency (IRENA) that in the next 10 years prices will drop another 60% (Reuters, 2020). The current spot price is US$0.30/W (PVInsight, 2020) allowing small to large scale PV to be competitive to conventional energy supplies and have an effect on the grid (Coughlin & Cory, 2009; Renewables; 2017, Polman et al., 2016; Safi, 2020). Financial factors, however, are key to profitability and have shifted due to government policy, access, and increasing efficiency (Coughlin & Cory, 2009;
Prehoda et al., 2019; Safi, 2020). While the cell costs have reduced, the installation, the balance of systems (BOS) costs have not changed to such a degree (Polman et al., 2016; Feldman et al., 2012). With module costs reducing and efficiency increasing, the BOS cost, has become an increasingly larger factor in the economics of PV systems.

Although, the modules have undergone extensive research and decreased in price, the rest of the system has swelled to over half of the cost with racking making up a large fraction (Fthenakis & Alsema, 2006; Feldman et al., 2015; PVinsight, 2020). Until recently this was not an issue because the relative costs of PV racking have been marginal and relatively little effort was made on reducing PV racking materials and costs (Feldman et al., 2012). This can be seen in the costs of racking summarized in Table 1. The most economical racking options in 2010 had a range of costs of $0.19/W to $0.44/W cost for ground mounts (CivicSolar, 2010). In 2017 NREL published the cost of racking to be between $0.22–0.31/W (Fu et al., 2017). Today the top brand (Wholesale, 2020) of small small-scale ground mount cost $0.366/W (SunWatts, 2020; IronRidge, 2019) and utility-scale racking costs $0.15-$0.20/W for driven piles and up to $0.23/W for concrete set (Myers, 2020; Pascaris, 2020). The recent percentage costs of racks and hardware BOS ranges from 12.6% in residential where racks may cost more than modules per W to 16.0% for commercial PV (Fu et al., 2017). Thus, racking costs are now reducing PV installation velocity as they are one of the bottlenecks in overall costs which limit the Sunshot 2030 goal of 3 cents per kWh for utility-scale PV (DOE, 2020).

Table 1. PV racking cost comparison.

<table>
<thead>
<tr>
<th>Racking Systems</th>
<th>Residential ($/W)</th>
<th>Commercial ($/W)</th>
<th>Utility ($/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 Ground mount 4.5kW scale (Civic Solar, 2010)</td>
<td>0.19-0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017 NREL national (Fu et al., 2017)</td>
<td>0.31</td>
<td>0.26</td>
<td>0.22</td>
</tr>
<tr>
<td>2020 Ground mount small scale (SunWatts, 2020; IronRidge, 2019)</td>
<td>0.366</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020 ground mount utility scale (Myers, 2020; Pascaris, 2020)</td>
<td></td>
<td>0.15-0.23</td>
<td></td>
</tr>
</tbody>
</table>

One of the demonstrated methods of reducing racking costs is to develop open source racking concepts and several types of PV racks have been developed including: RV rooftops (Wittbrodt, et al., 2015), low-tilt ground mounts for the developing world (Wittbrodt & Pearce, 2017), flat commercial rooftops (Wittbrodt & Pearce, 2015) and BIPV residential rooftops (Pearce et al., 2017). There has not, however, been a dedicated academic effort to developing solar farm racks to be low cost. Racking development has largely been carried forward by industry. The standard rack is proprietary and far costlier than the materials. In this project, unlike the conventional racking of solar panels in solar farm, a new method using shotcrete-based ground mounts will be investigated in two geographic regions: 1) Boa Vista, Brazil, which is near the equator where PV rows have an optimized shallow tilt angle and can be close-packed and 2) Kingston, Canada, which is at northern latitude, where racks can make use of low concentration in the necessary space between rows to avoid inter-row shading. After calculating optimal tilt angles and allowing for maintenance walkways, open source system design models are
developed in computer aided design (CAD) for single, double and triple vertical stacked shotcrete-based ground mounted PV racking systems. Using these models both bills of materials and energy production calculations for the two locations are produced to provide a cost benefit analysis specifically for the racks and then this is compared to conventional racking. The results of this analysis will be used to determine the techno-economic viability of this novel type of PV racking.

2. Methods

2.1 Geographic Analysis

To determine the geographic potential for a shotcrete-based ground mounted solar rack two locations are chosen 1) Boa Vista, Brazil (2.8235° N), which is near the equator where PV rows can be close-packed with a 5-degree tilt angle and 2) Kingston, Canada (44.2312° N), which is at northern latitudes where racks can make use of low concentration reflectors as shown in previous work (Andrews, et al., 2013; 2015).

Boa Vista is selected because of its proximity to the equator, relatively high irrandiance levels, and the city’s need for energy. This city has a population of 399,213 people and 1,900 sun hours annually (Brinkhoff, 2019; Weather, 2020). The tilt is calculated to be 5 degrees and inter row shading distance 0.0719 times the length of the module (White, 2016; NOAA 2020).

Kingston has a larger population of 590,940 people and 1,965 sun hours annually (World, 2020; Weather, 2020). This racking will apply/utilize previous calculations of location, reflector angles, and system performance modeling.

The difference between Kingston and Boa Vista’s annual sun hours is 3.3% making them roughly comparable from a PV systems perspective.

2.2 Design Technical Constraints

Ideally racking could be made from material on the installation site alone (i.e. earth) with no added racking. Real world earth, however, demands stabilization. Shotcrete is an ideal material to provide that stabilization because it can be applied quickly (Khitab, 2015), is applicable for variable slopes, frost enduring, environmentally sound, and durable over the long term (Brown, 2005; Bernard, 2007). The racking design will mount PV modules directly on the shotcrete with the following design constraints.

Crystalline silicon (c-Si)-based solar PV dominate the market, and they have a reduction in efficiency of 0.5% per degree Celsius (Weimar, 2016). In order to avoid excessive heating because of lack of convection on the backside, the modules will have an airflow gap beneath most of the module surface for passive cooling by careful shaping of the earth before shotcrete is conformally applied.

For maintenance the walkways and drainage are included. Walkways must be greater than 457.2 mm (OSHA, 1982), but are minimized at these values to optimize packing (W/m²) and reflectance. Deep drains may be needed in each row and spaced depending on the location and soil composition (Hagen & Cochran, 1996).
For the shotcrete systems at high latitudes a low concentration reflector system is used. A wide range of paints are suitable to apply to the shotcrete that will act as a low concentration reflector while scattering the light (Kinoshita & Yoshida, 2016; De Masi et al., 2018). This includes solar reflectant self-cleaning paint that will improve both mechanical durability and albedo (Wang et al., 2020). The V-shape, needed to replicate the low concentration geometry for PV (Andrews et al. 2013;2015) is feasible with widely accessible construction equipment. Grading costs are measured by the volume of earth moved or hours of construction (Schor & Grey, 1995; Deliberto & Hilbun, 2017) and are included in the racking cost estimates.

For this study Cheetah HC 72M 390-410W modules were selected from Jinko Solar, which is currently the top manufacturer (Jinko, 2020; EnergySage, 2019). The panels are 1002 mm x 2008 mm x 43.2 mm including the front glass. An extra 30 mm offset is added to each side edge of the array to allow space for fastening to the shotcrete.

Six shotcrete-based racking geometries systems are evaluated (shown schematically in the side view in Figure 1). Three models are analyzed with an increasing number of solar panels in the vertical stack of a row per V trench for use in Canada. These designs are appropriate for high northern or southern latitudes. Three more model are evaluated with one to three panels at a smaller tilt angle of 5° and no reflector for use in Brazil or other locations near the equator.

![Diagram of shotcrete racking geometries]

Northern Latitude 1 panel
Northern Latitude 2 panels
Northern Latitude 3 panels
Equator Latitude 1 panel
Equator Latitude 2 panels
Equator Latitude 3 panels
The shotcrete solar racking will be installed on shaped earth. The earth must be move into ridges to apply shotcrete similar to the V ditch process. The National Engineering Handbook Section 16 (NRCS, 2020) explains the steps as: soil sampling, land properties determined, corresponding requirements observed, and finally excavator cuts into the ground. Soil is sampled through boring to determine the land stability requirements before starting to excavate (Department of Transportation, 2015). To achieve a proper geometry a machine must manage cutting 2.65m down and 6.49m across the earth as well as being maneuverable between ditches following the low-concentration geometry of Andrews et al. (2011). An example machine of this size and maneuverability is the Caterpillar 313f GC (Caterpillar, 2015). The machine max depth of 6.02m and max reach of 8.61m. These limitations based on the design are not highly restrictive, even the soil can be altered to meet surface density requirements.

The PV modules are placed on the ground that has been shaped for the V grooves and then further formed with approximately module-width dugouts to allow for air circulation; covered in shotcrete; and finally attached via plates and steel wedge anchors into the shotcrete. This arrangement is shown in Figure 2 where the observer is at the side of the module (left) and then at the top of the module side of the V-groove looking down toward the bottom of the trench (right). To allow for passive cooling panels must be a minimum of 65mm offset (Saint et al., 2018; CivicSolar, 2017). Since the offset can vary depending on the local weather, to be conservative this design used 100 mm elevation.

2.3 Shotcrete

After the earth is formed by the excavator, the ground needs to be stabilized so that it does not change its shape due to wind or water erosion. Shotcrete can provide this stabilization. Historically it was used for repair solutions and temporarily in complex geometries because it does not need formwork. It is
viable in wider application due to advancements in flexural toughness, durability, and impact (Atef, 2016). Shotcrete sprayed 50 mm thick can have a tensile strength of 2 – 2.5 MPa; this is sufficient for desired structural support (Hoek, 2006). Shotcrete can be improved by additives or application processes. For this project the most optimal shotcrete is without synthetic fibers and no added accelerator (Gupta et al., 2000; Prudêncio, 1998). Drying time at these angels does not need to be improved and the absence of accelerators improves the durability. Synthetic fibers would improve the static load bearing, dynamic load, post crack strength, and life span, however, the difference will be negligible with a load this size.

For the designs with low concentration reflectors at 33.7°, the area of the reflector surface will not be bearing a load so 50 mm of shotcrete is unnecessary. Shotcrete is applied in some tunnels as thin as 10 mm (Austin et al., 1995). Therefore, reducing the thickness on the reflector surface only from 50 mm to 10 mm will also be calculated to reduce materials used, coating time, and cost.

2.4 Adapter Plates

The panels are required to directly attach to the shotcrete foundation for adequate stability using adaptive brackets. For this external mounting, with the panel extended from the surface in the x plane, adapter plates and steel wedge anchor are recommended by EJOT (EOJT, 2020). Plates can directly mount to the foundation with bolt plates unlike the more common but costly rail systems (Salama, 2018). This plate is shown in Figure 3.

![Figure 3: Perpendicular view (sun view) of mounting plate and module with racking attachment to mounting plates](image)

2.5 Steel Wedge Anchors

All soil is made up of a mixture of sand, silt, clay, and rock in different ratios. Shotcrete can adhere to any of these mediums due to its versatility and original design to be in tunnels and eroded structures (USACE, 2005). The best option would be a cohesive loam (mixed) soil so it is easily moved by
excavators, stable, and able to drain water (Palmer, 2018). Soil is also classified by A, B, and C soils based on the composition and strength; type B soil is best, but all are feasible for shotcrete application (OSHA, 2020).

Wedge anchors are essential to stabilizing the solar array to the shotcrete. A ¼” Trubold Wedge anchor (RedHead, 2020) was chosen because it is tested to have a 43.4 Mpa compressive force, 76.2mm embedded depth, and combined is able to withstand 4,500 kN of tensile force. The pull-out force is between 7.59-9.57 kN depending on the shotcrete. The force on a module due to wind on the plate is represented with the aerodynamic drag equation for a flat plat:

\[ F_{\text{module}} = P \cdot A \cdot C_d \, [\text{N}] \]  

where the pressure of air (P) going 100mph to represent the worst-case scenario is 245.15 N/m², the area of the plate is the area of the module (A) is 2.01 m², and the drag coefficient (C_d) can be approximated to be 1. Each module is attached to the shotcrete with 4 steel wedge anchors, so the total force, divided by 4 anchors per panel, is 1,233 N, which is less than a third of the rated tensile strength and a sixth of the pull-out strength of the steel wedge anchors.

2.6 Energy Simulations

Energy output for the six design geometries was calculated with NREL’s Solar Advisory Model (SAM), for the PV modules without reflectors, considering row shading, reflection, soiling, inverter losses and clipping, wiring, and local weather data (NREL, 2020). To represent row shading a vertical box was designed at a height and offset to represent the geometry of the system. Other losses such as panel degradation, inverter losses, wiring losses, soiling, and reflection are based on SAM standard baseline values. For the Kingston system 3% snow losses were included based off of past experimental results (Andrews & Pearce, 2012; Andrews et al, 2013). For the low-concentration systems the values of reflector gain previously calculated and experimentally validated by Andrews et al. (2015) were utilized of 18% gain for low-cost white paint reflectors and 30% gain for high-end engineered reflectors.

3. Results

3.1 Design

The space between the rows of PV will also be dug and stabilized by shotcrete in order to utilize the solar radiation falling in between racks. After stabilization low level concentrators are placed on this area (e.g. white paint) or an engineering grade reflector (e.g. Reflectech).

The models at 5° and at 33.7° with one module will only have one walkway of 750 mm. This is because the modules can be easily reached and serviced with only one walkway. The models at 33.7° with 2-3 modules will have two walkways so the panels can be serviced safely. This can be seen in Figure 4.
Figure 4: Main view of 3 rows by 3 columns of modules
In Figure 5, the end of a row can be seen, the plates attach the module to the shotcrete ridges. The solar panel is 1002 mm wide with a lip indented 55 mm (seen with hidden lines). The holes to secure the panel are 324 mm x 45 mm into the frame. There is a 30 mm gap along the width of the module and the shotcrete due to the plate to mount the module. It can also be seen in Figure 6 (side view 1 module 5 degree tilt) that there is a gap of 4.83 mm for the thickness of the plate. Figure 7 shows the side view of the high latitude 2 module design to scale and Figure 8 shows the top view of the 3 modules low-concentration system. Figure 3-8 are all at scale.
A single acre solar farm with this setup will allow for a 63.6 m by 63.6 m grid that will allow for 32 columns of solar panels over a 4047 m² area. Each of the six designs evaluated here is optimized with different numbers of rows and columns to closest match one acre and stay within ±4 rows of the optimum 32. By adjusting the column count the error in area is less than a third of a percent. The designs of a single acre shotcrete solar farm are summarized in Table 2.

Table 2. Designs specifications for a 1-acre solar farm for the six geometries of shotcrete PV racking for 410W modules.

<table>
<thead>
<tr>
<th>Design</th>
<th>Number of rows</th>
<th>Panels/row</th>
<th>Number of columns</th>
<th>Number of PV modules</th>
<th>Power [W/ac.]</th>
<th>Area [m²]</th>
<th>Area error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 panel 5°</td>
<td>37</td>
<td>1</td>
<td>30</td>
<td>1110</td>
<td>455,100</td>
<td>4048</td>
<td>0.02</td>
</tr>
<tr>
<td>2 panel 5°</td>
<td>20</td>
<td>2</td>
<td>35</td>
<td>1400</td>
<td>574,000</td>
<td>4051</td>
<td>0.10</td>
</tr>
<tr>
<td>3 panel 5°</td>
<td>15</td>
<td>3</td>
<td>34</td>
<td>1530</td>
<td>627,300</td>
<td>4043</td>
<td>0.09</td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>21</td>
<td>1</td>
<td>36</td>
<td>756</td>
<td>309,960</td>
<td>4045</td>
<td>0.05</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td>13</td>
<td>2</td>
<td>29</td>
<td>754</td>
<td>309,140</td>
<td>4034</td>
<td>0.32</td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td>9</td>
<td>3</td>
<td>31</td>
<td>810</td>
<td>343,170</td>
<td>4058</td>
<td>0.27</td>
</tr>
</tbody>
</table>

3.2 Capital Costs

With each the configurations the materials and components needed along with their associated costs are shown in Table 3. Each component is assessed per unit or per one solar panel then calculated for 1 acre. After the solar panels, paint, and hardware, the shotcrete, labor, and grading are calculated. Land
clearing and shaping cost $100-150/hour and 40 hours/acre averaging $5,200/acre (Homeadvisor, 2020). Competitive shotcrete and installation estimates are from Kalmatorn, extrapolated from a 25.4mm model (Kalmatorn, 2020). Shotcrete of 50 mm thick and installation cost $12.51/m². Table 4 sums the total cost for each geometry of shotcrete racking per acre. Furthermore, the cost per Watt is calculated.

Table 3. Bill of materials of basic components and capital costs

<table>
<thead>
<tr>
<th>Design</th>
<th>Component</th>
<th>Number per Acre</th>
<th>Cost per Module</th>
<th>Total Cost per Acre</th>
<th>Source of cost information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 panel 5°</td>
<td>Cheetah HC 390M-72HL-V Solar Panel</td>
<td>1110</td>
<td>$249.60</td>
<td>$277,056.00</td>
<td>(Solar, 2020)</td>
</tr>
<tr>
<td>2 panel 5°</td>
<td></td>
<td>1400</td>
<td></td>
<td>$349,440.00</td>
<td></td>
</tr>
<tr>
<td>3 panel 5°</td>
<td></td>
<td>1530</td>
<td></td>
<td>$381,888.00</td>
<td></td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>White reflective paint, Exterior and Latex Base</td>
<td>0</td>
<td>$15.025</td>
<td>$0</td>
<td>(Grainger, 2020d)</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td></td>
<td>0</td>
<td></td>
<td>$0</td>
<td></td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td></td>
<td>0</td>
<td></td>
<td>$0</td>
<td></td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>Bolts and nuts 1/4”-20 Steel hex, grade 2, 1-1/4” L</td>
<td>4440</td>
<td>$0.298</td>
<td>$330.51</td>
<td>(Grainger, 2020b)</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td></td>
<td>5600</td>
<td></td>
<td>$416.86</td>
<td></td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td></td>
<td>6120</td>
<td></td>
<td>$455.57</td>
<td></td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>Adapter Plate, stainless steel 0.19”x1.18”x3.23”</td>
<td>4440</td>
<td>$8.650</td>
<td>$9,601.94</td>
<td>(Grainger, 2020a)</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td></td>
<td>5600</td>
<td></td>
<td>$12,110.56</td>
<td></td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td></td>
<td>6120</td>
<td></td>
<td>$13,235.11</td>
<td></td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>Red Head Wedge Anchor 3-1/4”, ¼” L</td>
<td>4440</td>
<td>$2.200</td>
<td>$2,442.00</td>
<td>(Grainger, 2020c)</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td></td>
<td>5600</td>
<td></td>
<td>$3,080.00</td>
<td></td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td></td>
<td>6120</td>
<td></td>
<td>$3,366.00</td>
<td></td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>Shotcrete 8,357.84m²</td>
<td></td>
<td>$35.09</td>
<td>$38,954.03</td>
<td>(Kalmatorn, 2020)</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td></td>
<td></td>
<td></td>
<td>$38,954.03</td>
<td></td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td></td>
<td></td>
<td></td>
<td>$38,954.03</td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Bill of materials summary of shotcrete, installation and labor, and hardware costs.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Low Cost</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost per acre</td>
<td>Cost per acre</td>
</tr>
<tr>
<td></td>
<td>$/W</td>
<td>$/W</td>
</tr>
<tr>
<td>1 panel 5°</td>
<td>$69,895.91</td>
<td>$71,495.91</td>
</tr>
<tr>
<td></td>
<td>$0.154/W</td>
<td>$0.157/W</td>
</tr>
<tr>
<td>2 panel 5°</td>
<td>$73,817.78</td>
<td>$75,417.78</td>
</tr>
<tr>
<td></td>
<td>$0.129/W</td>
<td>$0.131/W</td>
</tr>
<tr>
<td>3 panel 5°</td>
<td>$75,459.04</td>
<td>$77,059.04</td>
</tr>
<tr>
<td></td>
<td>$0.120/W</td>
<td>$0.123/W</td>
</tr>
<tr>
<td>1 panel 33.7° w/ reflector</td>
<td>$64,653.42</td>
<td>$90,458.27</td>
</tr>
<tr>
<td></td>
<td>$0.209/W*</td>
<td>$0.292/W*</td>
</tr>
<tr>
<td>2 panel 33.7° w/ reflector</td>
<td>$64,494.02</td>
<td>$90,234.84</td>
</tr>
<tr>
<td></td>
<td>$0.209/W*</td>
<td>$0.292/W*</td>
</tr>
<tr>
<td>3 panel 33.7° w/ reflector</td>
<td>$65,852.12</td>
<td>$94,250.34</td>
</tr>
<tr>
<td></td>
<td>$0.192/W*</td>
<td>$0.275/W*</td>
</tr>
</tbody>
</table>

* includes additional reflector costs

As can be seen in Table 4, the most economical model is with 3 panels at 5°. The variation in excavation costs cause a difference of $0.003/W in the 5° geometry and $0.005/W in the 33.7° geometry. The 1 and 2 panel geometries at 33.7 are highly similar in cost due to going from 1 to 2
walkways per row for maintenance. The total range of cost per Watt for all the models is $0.120/W – $0.209/W. Reducing the shotcrete thickness on the reflector surface reduced the cost by $32.01 per module in materials and labor costs.

3.3. Energy Output

The results of the SAM simulations show that a single module is projected to produce 623 kWh per year at the 5-degree angle in Boa Vista, Brazil and 548 kWh per year at 33.7-degrees in Kingston, Canada. Shading in these configuration as shown in Table 5 accounts for a 1.1% and 0.2% energy loss, respectively. The yield per acre, however, is greater in Boa Vista as can be seen in Table 6. The modules with low concentration reflectors have energy calculations based off a previously tested model at the same latitude and therefore equal packing, tilt angle, and solar panel to reflector space ratio of 1:1.5 (Andrews, et al., 2011). The reflectors improve the energy output by 18% in this model which utilizes basic white latex concrete matte paint. A maximum of 30% is possible in this location with a reflector material having a higher reflectance. The panels are at an angle of 33.7% (Andrews et al., 2015). Additional thermal losses are avoided as the modules are elevated from the shotcrete to allow for sufficient ventilation similar to the outdoor testing in the Open Solar Outdoors Test Field (OSOTF) in Canada (Pearce, et al., 2012). With an 18% gain in Kingston with a white paint reflector the yield increases to 646 kWh/year and up to 712 kWh/year using an ideal reflector. For Boa Vista the same module produces less energy on a per module basis. These close-packed low-tilt angle systems, however, allow for many more modules per acre and thus produce more energy per acre than the less densely packed systems at high latitudes – even when using high reflectance low concentration.

Table 5. SAM annual energy calculation parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>Panel</th>
<th>Inverter</th>
<th>Shading height</th>
<th>Shading offset</th>
<th>Shade loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>Jinko Solar: JKM 410M-72HL-V</td>
<td>SunPower: SPR-E20-245-A-AC</td>
<td>0.0926 m</td>
<td>0.7581 m</td>
<td>1.084%</td>
</tr>
<tr>
<td>33.7° w/reflector</td>
<td></td>
<td></td>
<td>0.884 m</td>
<td>2.075 m</td>
<td>0.189%</td>
</tr>
</tbody>
</table>

Table 6. Energy (kWh per year) analysis including reflectance for the 6 shotcrete systems.

<table>
<thead>
<tr>
<th>Model</th>
<th>Annual Energy per module (kWh)</th>
<th>Reflector Multiplier</th>
<th>Modules per acre</th>
<th>kWh/year per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 panel 5°</td>
<td>623</td>
<td>1</td>
<td>1,110</td>
<td>691,530</td>
</tr>
<tr>
<td>2 panel 5°</td>
<td></td>
<td>1</td>
<td>1,400</td>
<td>872,200</td>
</tr>
<tr>
<td>3 panel 5°</td>
<td></td>
<td>1</td>
<td>1,530</td>
<td>953,190</td>
</tr>
</tbody>
</table>
As can be seen in Table 7, the shotcrete-based racking system can cost less than even the least expensive utility-scale racking system identified. The most economical shotcrete model evaluated, 3 panel at 5° tilt angle, is at least $0.03/W less expensive per W than current racking system being employed and can be half the cost of the more expensive systems. Thus close-packed low-tilt angle shotcrete racking could decrease racking costs by 20%. The open source shotcrete racking models at 33.7° with reflectors can be 16% less expensive than the most expensive conventional racking, but this shotcrete rack design does have higher capital costs than current lowest-cost utility-scale racking. It should be noted; however, this system has increased output and potential to reduce soiling need to be considered to fully analyze the economics. Future experimental work is needed to fully evaluate these systems. The geometries of 2-3 panels at 5° are both less expensive than the least expensive racking in 2020 and are realistic to implement in equatorial regions particularly in desert areas as discussed below.

### 4. Discussion
As can be seen by the results the installation of shotcrete mounted solar modules is economically feasible and may be of assistance in further driving down the cost of solar electricity in some areas. The theoretical calculations and analysis performed in this study warrants experimental verification in future work. It should also be pointed out that the costs of these systems are conservative as a large-scale developer would have economies of scale potential to drive down costs further. There is also potential for vertical integration (e.g. a developer bringing excavation and shotcrete deposition in house), which has the potential to further reduce costs. Although the results indicate that shotcrete is economical it involves expertise to install and could be a limiting factor depending on availability. In addition, depending on the soil type and water table at the installation location, measures may need to be taken to reduce the economical footprint as well as ensure protection from water and flood damage. In preliminary analysis gutters were found not to be optimal, but periodic drains and a perimeter drain plan can be implemented and should be studied in future work. Deep rooted grasses along the edges would greatly reduce the runoff and improve retaining water, nutrients, and minerals on site (Hagen & Cochran, 1996; Rushton, 2002) and thus should also be considered depending on the location.

Considering the environmental impact, which is left for future work, siting of such shotcrete-based arrays must be done with care. Concrete has a high embodied energy and emissions (Wu et al., 2014) although this may be reduced for ‘green shotcrete’ with recycled silica fume and fly ash (Badr, 2009). Regardless covering fertile ground with shotcrete may be counterproductive. Land with idle ground is ideal due to the nature of using shotcrete whereas fertile ground would be better suited for dual use agrivoltaics where both solar electricity and a crop can be harvested from the same area (Dupraz et al., 2011; Dinesh and Pearce, 2016; Santra et al., 2017; Malu et al., 2017; Amaducci et al., 2018). By using uncomplicated grading, simple sprayable concrete, white paint, and basic hardware the model can be implemented all over the world. This type of shotcrete-based racking system is perhaps best suited to locations where the ground results in additional soiling losses (Pavan et al., 2011; Appels et al., 2013) such as sand effects in desert environments (Mohamed and Hasan, 2012; Semaoui et al., 2016; Bouraiou et al., 2015). It is presumed that for large solar farms shotcrete-based racking would reduce dust and soil related losses. Future work is needed to evaluate this potential advantage experimentally.

The natural panel cooling, built in reflectors, and durability of this design concept reduces maintenance and component failure, but again calls for future work to ensure that there are not additional thermal losses or other negative effects on PV performance in shotcrete-based arrays both with and without reflectors. Future work is also needed to determine the optimal reflector coating for shotcrete-based PV racking. In addition, as with some other open source racking designs (Pearce et al., 2017) modules with the frame turned out rather than in would reduce racking cost and installation times. Future work is needed to evaluate the viability of altering PV frames. Finally, in the future the model can be improved with better reflectors, cooling systems, or snow removal implementation depending on the climate.

6. Conclusions

This study has provided a new PV racking method using shotcrete-based ground mounts. The analysis
found that the systems were economically viable throughout the majority of latitudes for which solar PV are deployed. For systems at high latitudes low-concentration is feasible by applying reflective paint directly to the shotcrete to benefit from enhanced albedo gains. The open source system design models provided in this study are a good starting point for future experimental work needed to verify the economic results, which indicated that for utility-scale PV systems near the equator a shotcrete racking system could reduce racking costs by 18% to 22% from the least expensive conventional racking and as much as 47% for more expensive commercial racking. The economics of shotcrete-based racking at higher latitudes that incorporate low-concentration reflectors are less clear as the capital costs can be less expensive than the most expensive conventional racking, but are more expensive than the least expensive conventional racking. The shotcrete systems with low concentration reflectors, however, would be expected to produce at least 18% more electricity than those mounted in conventional racks. This type of shotcrete-based racking system is perhaps best suited to locations where the ground results in additional soiling losses such as deserts. Overall, this novel racking concept is promising and the results of this study indicate a need for future work to fully evaluate the potential to reduce solar electricity costs at the utility scale.

Acknowledgments

This research was funded by the Witte Endowment and helpful discussions with M. O'Brien and H. Basireddy.

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