Test and Evaluation of the Solarstone Solpaver Product

Cooperative Research and Development Final Report

CRADA Number: CRD-20-16730

NREL Technical Contact: Bill Marion

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5K00-81031
September 2021

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Cooperative Research and Development Final Report

Report Date: September 20, 2021

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Solar Hardscapes, LLC

CRADA Number: CRD-20-16730

CRADA Title: Test and Evaluation of the Solarstone Solpaver Product

Responsible Technical Contact at Alliance/ National Renewable Energy Laboratory (NREL):

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Name and Email Address of POC at Company:

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources	Totals
Year 1	$75,000.00	$75,000.00
TOTALS	$75,000.00	$75,000.00

Executive Summary of CRADA Work: NREL will establish the mechanical, thermal, and electrical characteristics of the Participant’s triple composite Solarstone Solpaver unit, compare to the same characteristics of an identical non-triple composite PV module, and summarize the results.

<u>Summary of Research Results</u>:

NREL Tasks:

Task 1. NREL will perform a mechanical load test of the Participant's product to point of failure or 750 pounds per square foot (psf) and compare to the same test of an identical non-triple composite PV module. Electrical continuity during the load test and before and after electroluminescence images and hi-pot tests are part of the load test to detect changes in the electrical integrity.

The participant's triple-composite product for the load test used a 50-watt module normally intended for recreational purposes such as low-voltage battery charging. Because these types of modules do not have a load rating, we used a commercial PV module load rating of 5400 Pa (113 psf) for comparative purposes rather than perform a load test on the non-triple composite PV module. Also, to accommodate available equipment and safety concerns, and upon mutual agreement of both parties, the load applied to the modules was reduced from 750 psf to 750 pounds total, which equates to 183 psf for the module area of 4.1 ft^2. This load is about 60% greater than the commercial PV module load rating. The load was also applied with the PV module supported at the four corners, which supplies significantly more stress than if the PV module is uniformly supported by the ground as it would be in a paver-type installation.

An image of the triple composite PV module undergoing the load test is shown in Fig. 1. The 183 psf load was applied three times for an hour duration, with a 30-minute rest period between load applications. The PV module successfully passed the load test. No mechanical failures or changes in electrical continuity were observed during the load test. As shown in Fig. 2, the electroluminescence image recorded after the load test did not indicated any significant cell cracking. The PV module passed both the before and after wet-hipot tests, with resistance values of greater than 10 giga-ohms and greater than 7 megaohms, respectively.

Fig. 1. Participant's product undergoing the load test. The PV module and load are contained in cloth bags for safety purposes in the event of a PV module or load testing method failure.

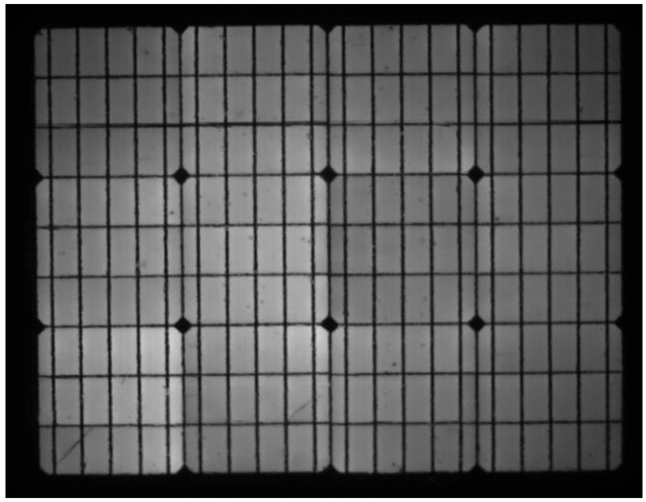

Fig. 2. Electroluminescence image recorded after the load test shows no significant cell cracking.

Task 2. NREL will perform an outdoor electrical energy output tests for a minimum of one month comparing a patio type installation of the Participant's product and an identical non-triple composite PV module mounted on an asphalt shingle sloped roof.

A set of PV modules were installed for the outdoor tests on February 20, 2021. Unfortunately, it was soon observed that the front composite cover was delaminating from the PV module glass surface. The participant indicated that this was from the AR coating on the glass not being removed prior to applying the front composite material. A new set of products was sent to NREL that were made using an improved process to remove the AR coating from the glass prior to applying the front composite material. These products were installed on April 8, 2021, and are shown in Fig. 3. Some delamination is still evident, but not as severe as the original products. The new PV modules have a nominal power rating of 100 W and were maintained at their maximum power point with electronic loads and their electrical output was recorded continuously, except from April 12 through April 26 when the triple composite PV modules were temporarily removed for the immersion test in Task 5.

Fig. 3. Triple composite PV modules installed on ground as pavers (left) and a non-triple composite PV module mounted on an asphalt shingle sloped roof surface (right). Corresponding to their data logger channel assignment, the left paver module is referred to as M102 and the right paver module is referred to as M104. More delamination is evident for M104 on the right.

The outdoor electrical performance test was performed for the month of May 2012. Fig. 4 illustrates the average hourly irradiances incident the PV modules and the power outputs. Because of the sun position at this time of year, the horizontal PV module pavers receive more irradiance than the PV module on the sloped roof. But this did not translate to a greater power output because of transmittance losses associated with the front composite cover and delamination, which was more problematic for M104.

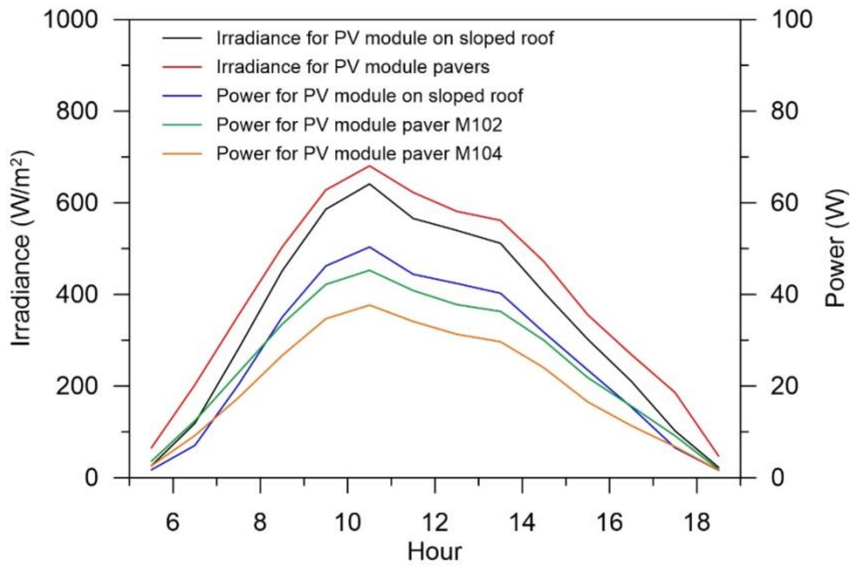

Fig. 4. Average hourly profiles for May 2021 showing PV module irradiances and power output.

By normalizing the performance with respect to irradiance, the performance ratio (PR) quantifies the overall effect of losses with respect to the module rated power. These losses include the effects of temperature and in the case of the PV module pavers, the transmittance losses associated with the front composite cover and delamination. Fig. 5 illustrates average hourly PR values for the month of May.

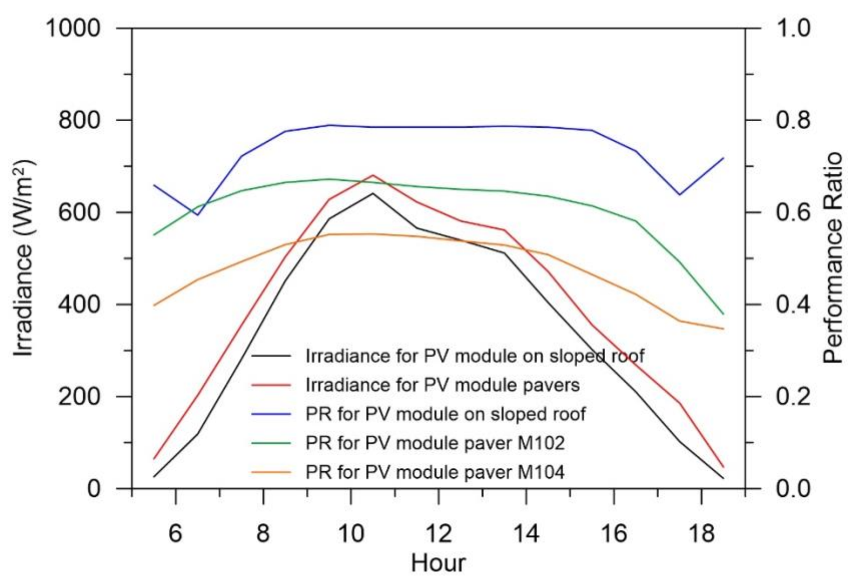

Fig. 5. Average hourly profiles for May 2021 showing PV module irradiances and performance ratios.

The monthly irradiances, energy production, and PRs are listed in Table 1. For May, the irradiance for the horizontal paver PV modules is about 16% greater than for the sloped roof PV module. On an annual basis for this location, the reverse would be true with the irradiance for the sloped roof PV module about 20% greater than for the horizontal paver PV modules. PRs are normalized with respect to irradiance and are a useful metric for comparing the PV module outputs relative to their rated power.

Table 1. Irradiance, PV Module Energy Production, and Performance Ratio for May 2021 for the PV Modules.

PV Module	Irradiance (kWh/m2/Day	Energy Production (Wh/Day)	Performance Ratio (dimensionless)
Sloped Roof	4.763	366.5	0.769
Paver M102	5.529	353.2	0.639
Paver M104	5.529	283.6	0.513

Task 3. Using the data from Task 2, NREL will compare the diurnal temperature profile of the Participant's product to an identical non-triple composite PV module mounted on an asphalt shingle sloped roof. Thermal images will be taken to illustrate temperature variations across the front surface of the Participant's product and the identical non-triple composite PV module.

Thermal images were recorded on April 30 and are shown in Fig. 6. Wind was from the east at slightly less than 2 m/s which corresponds with the east (right) edges of the modules exhibiting cooler temperatures. Irradiance at the time of the images was 912 W/m^2 (at 10:20 MST) for the modules installed as pavers and 982 W/m^2 (at 13:22 MST) for the module installed on the sloped roof. From the images, the representative temperature for the modules installed as pavers is about 42°C and for the module installed on the sloped roof is 39°C. The corresponding measured back surface temperature using a thermocouple for the module installed on the sloped roof was 45°C; consequently, there is some inherent error when determining temperature from thermal images. Back surface temperatures of the triple composite modules were not located sufficiently close to the PV cells to provide an accurate cell temperature. These measurements were more aligned with the ground temperature under the modules and had values of about 28°C, which was about 4°C greater than the ambient air temperature.

Operating voltage is also indicative of temperature and is shown in Fig. 7 for April 30 for the triple composite PV modules installed on ground as pavers and a non-triple composite PV module mounted on an asphalt shingle sloped roof surface. During midday when most of the energy is produced, all the modules exhibit similar voltages which indicates their cell temperatures are similar.

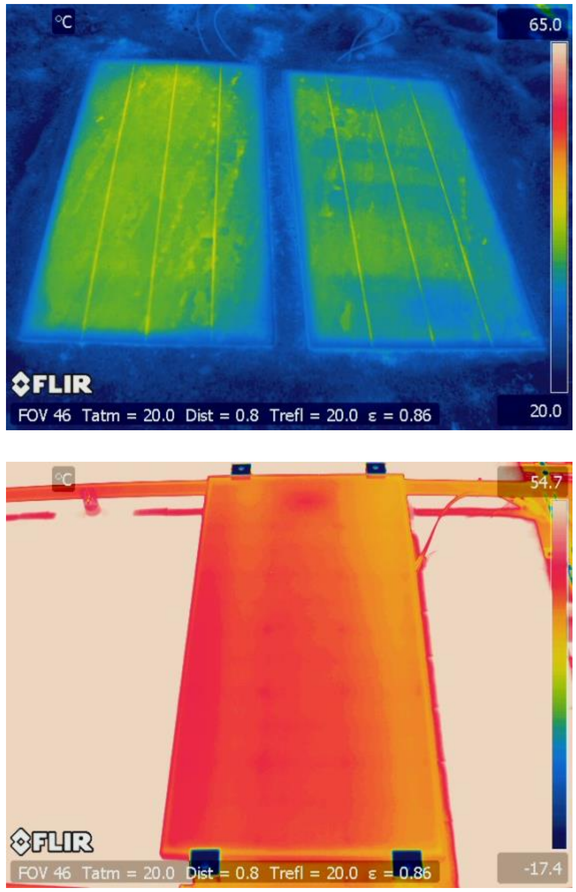

Fig. 6. Thermal images of the triple composite PV modules installed on ground as pavers (left) and a non-triple composite PV module mounted on an asphalt shingle sloped roof surface (right). When comparing temperatures, please note the different scaling.

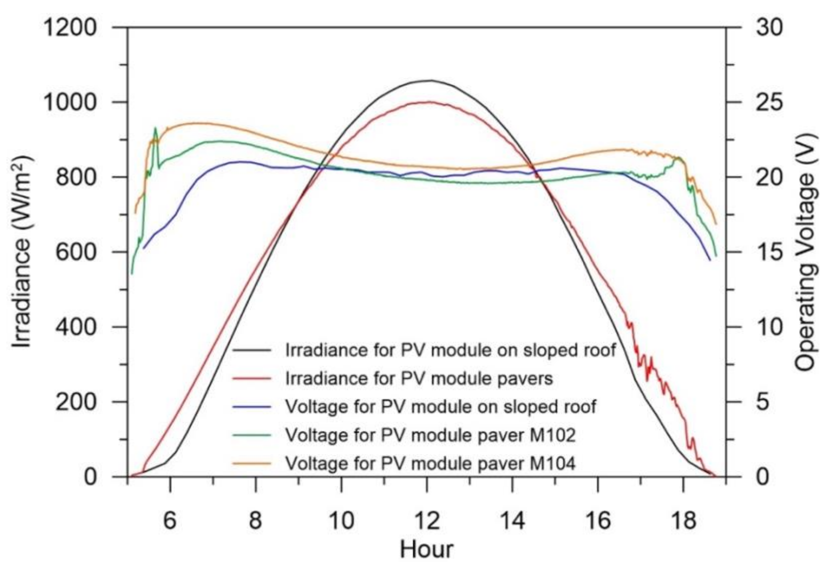

Fig. 7. Operating voltages of the triple composite PV modules installed on ground as pavers and a non-triple composite PV module mounted on an asphalt shingle sloped roof surface for April 30, 2021.

Task 4. Using the data from Task 2, NREL will compare the angular response due to sun position of the Participant's product to an identical non-triple composite PV module mounted on an asphalt shingle sloped roof to determine if the clear resin front surface provides additional benefit for energy production because it refracts the sunlight in a favorable manner similar that for tracking.

The angular response was evaluated for the morning of April 10, 2021. The morning of this day had clear skies with a large direct normal radiation component. Angular response is primarily a function of reflection from the front cover of the PV module which increases as the angle-of-incidence of the direct normal radiation increases. The losses are greatest in the morning and evening and less at midday when the angle-of-incidence is less.

The ratios of PV module power to irradiance as a function of the angle-of-incidence are shown in Fig. 8. In the figure, a larger ratio indicates less reflection loss. The range of angle-of-incidence values for the PV module on the sloped roof is greater because its tilted orientation promotes smaller angles near noon. This module has a typical angle-of-incidence response with increasing losses for angles greater than about 60°.

The two triple composite PV modules show different angle-of-incidence responses, with M104 which has more delamination having the poorer response. As discussed in Task 5, these PV modules also experienced glass breakage with may have altered angle-of-incidence responses. The additional clear resin front cover will reduce the PV module output for smaller angle-of-incidences because it absorbs some radiation. A benefit for energy production because it refracts the sunlight in a favorable manner was not demonstrated.

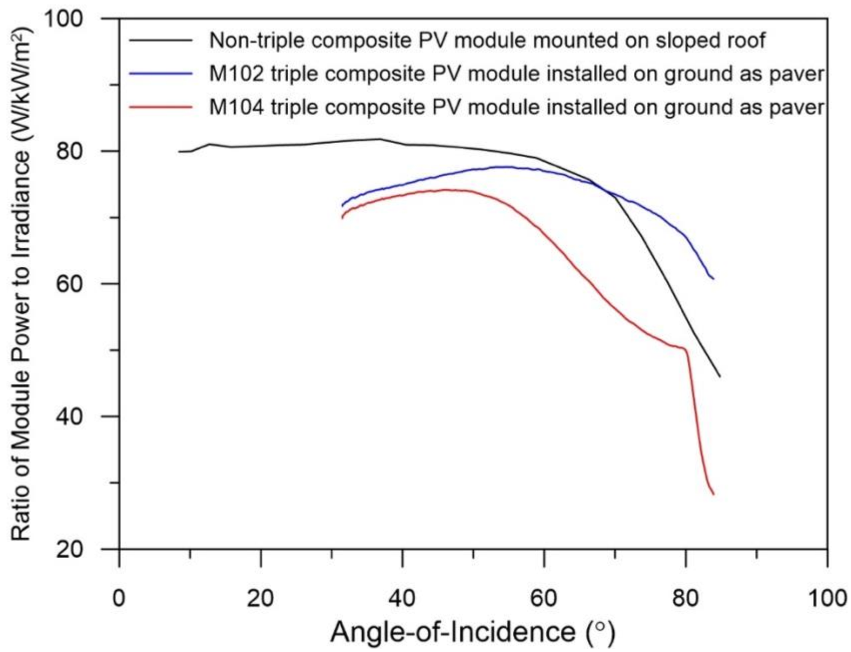

Fig. 8. Ratios of PV module power to irradiance as a function of the angle-of-incidence. A larger ratio indicates less reflection loss.

Task 5. NREL will perform a submerged water test to demonstrate applicability to Ingress Protection (IP) 68 where the Participant's product is submerged under one meter or more of water for greater than 30 minutes. The immersion test shall be conducted once for a duration of one hour. Energy production before and after the test will be measured and compared to another of the Participant's product which is installed for a patio configuration and not undergoing the submerged water test.

Although not planned, we performed the immersion test on both triple composite PV modules because of a difficulty when testing the first PV module. Upon removal of the first PV module from the immersion tank, it was observed that the glass part of the module was shattered (but still contained between the composite layers). The water in the tank was about 15°C colder than the PV module when initially submerged, so we speculated that a sudden change in temperature may have resulted in the failure. The second PV module was tested with its temperature the same as the water. After the immersion for one hour, the triple composite PV module was removed, and the glass part of the module was also observed shattered. The shattered glass is more visible when slightly under water. We think that the shattered glass was likely present before beginning the immersion tests, but not seen because of the difficulty in seeing through the composite front cover. The glass may have shattered during the preceding outdoor exposure because of differences in thermal expansion of the glass and the composite front cover. The thermal expansion of an epoxy is about a factor of seven greater than glass.

With both triple composite PV modules being immersion tested, we no longer had a reference module for the comparative before/after energy production. However, we are confident that the energy production of the triple composite PV module was not adversely affected by the immersion test because the module passed a wet hi-pot test both before and immediately after the immersion, which verifies that the electrical integrity of the PV module was not compromised.

Task 6. NREL will develop a performance report describing the results of the above performance tests to include thermal images, graphed data and the raw data.

A report describing the results of the performance tests performed for the preceding tasks was provided the participant on June 22, 2021, and summarized in this report.

Task 7. NREL will provide design consultation for refinements to the Participant's product.

The following design considerations were provided to the participant.

- The thermal expansion of the front composite cover is significantly more than the PV module glass and is likely the cause of the delamination, and perhaps the fracturing of the PV module glass. A possible solution might be to eliminate the need of the composite front cover by constructing a PV module with glass with a thickness and temper to achieve the desired strength (perhaps a glass/glass module construction).
- The wiring and connectors will need to be rated for direct burial to operate safely under conditions of rain and other conditions that saturate the soil with water, such as flooding.
- Shading from natural and manmade objects will need to be considered when locating the pavers, and shade tolerance should be part the electrical design.

Task 8. The Principal Investigator agrees to provide the following to DOE Office of Scientific and Technical Information (OSTI): (1) an initial abstract suitable for public release at the time the CRADA is executed; (2) a final report, within thirty (30) days upon completion or termination of this CRADA, to include a list of Subject Inventions; and (3) other scientific and technical information in any format or medium that is produced as a result of this CRADA.

The above items were provided. This CRADA Final Report (CFR) meets these requirements for publishing on the OSTI site.

Participant tasks:

Task 1. The Participant will participate in a monthly check-in with the NREL Principal Investigator. If a check-in meeting is missed two months in a row, the agreement may be cancelled by the American-Made Challenges Solar Prize team.

The participant satisfactorily participated in all check-ins and meetings requested by the NREL Principal investigator.

Task 2. The Participant will provide Participant's product and comparative products to be tested to the NREL site.

The participant provided all necessary products for testing, and also their replacements when the first set of products experienced delamination.

Task 3. The Participant will provide the electrical and mechanical specifications of the Participant's product and comparative products to be tested to facilitate NREL's design of the load test device and their installation for the other specified tests.

For the electrical and mechanical specifications, NREL used the nameplate information from the products provided by the participant for testing.

Subject Inventions Listing:

None

ROI #:

None