Validation of Silevo Modules at the Regional Test Centers

Cooperative Research and Development Final Report

CRADA Number: CRD-15-589

NREL Technical Contact: Chris Deline

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5K00-76254
March 2020

Validation of Silevo Modules at the Regional Test Centers

Cooperative Research and Development Final Report

CRADA Number: CRD-15-589

NREL Technical Contact: Chris Deline

Suggested Citation
Deline, Chris. 2020. *Validation of Silevo Modules at the Regional Test Centers: Cooperative Research and Development Final Report, CRADA Number CRD-15-589.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5K00-76254. https://www.nrel.gov/docs/fy20osti/76254.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5K00-76254
March 2020

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Cooperative Research and Development Final Report

Report Date: **1/30/20**

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA 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: Silevo, Inc. (acquired by Tesla)

CRADA Number: CRD-15-589

CRADA Title: Validation of Silevo Modules at the Regional Test Centers

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$100,000.00
Year 2, Modification #2	$20,000.00
Year 3, Modification #3 & 4	$24,000.00
TOTALS	$144,000.00

Abstract of CRADA Work:

Silevo and the National Renewable Energy Laboratory (NREL) are entering into a cooperative research and development agreement (CRADA) in order to perform validation testing of Silevo's Photovoltaic (PV) modules through the Department of Energy (DOE) Regional Test Center (RTC) program. This CRADA describes testing activities conducted specifically at the NREL-managed Colorado RTC site.

Summary of Research Results:

The RTCs conducted field trials to quantify the performance of Silevo's high-efficiency Silicon-Heterojunction (SHJ) PV modules (H60, H60 bifacial and WR320) vs conventional panels (Trina 255). Four specific tasks were conducted, as described below: Design, Construction, Data Acquisition and Analysis, and Final Report. Through the process of the project, a custom PV installation was designed and installed for Silevo / SolarCity, and six reports issued including a final close-out report.

Based on the first 2 years of system performance (June 2016 - September 2018), the following characteristics stand out:

- Measured performance was within 3.5% of modeled expectation for three module types (Trina 255, H60 monofacial, H60 bifacial)
- The Silevo WR320 string operated within 5% of expectation during the valid months, and is now closer in performance to the H60 string.
- Bifacial response of the bifacial H60 string was 6.4% above the monofacial H60 string, which is within expectation based on measured rear-side irradiance.
- The H60 monofacial string was found to have greater than stated temperature coefficient of power (−0.31%/C vs. −0.26% / C stated).

Task 1: Design

In this task, NREL worked with Silevo (subsequently purchased by SolarCity) to develop a technical validation plan. This document went through 5 revisions starting 16 June 2015 and was issued in a final version on 29 September 2015. This document was the controlling document for subsequent validation testing and was largely adhered to.

Initial project technical design was initiated April 2015 to establish technical scope and requirements for the partner. See Table 1 here and Figures 1 and 2 in Task 2.

Table 1. System summary information.

System parameter	**System Spec**			
Array tilt angle	30°			
Array azimuth:	180° (S)			
Altitude (ft)	5790			
Site Latitude	39.7403			
Site Longitude	105.6217			
Module Parameter	**String 1**	**String 2**	**String 3**	**String 4**
Manufacturer	Trina	SolarCity	SolarCity	SolarCity
Module Type	TSM255	H60 280	H60 280 Bifi	W320RW
Technology	mc-Si	HJT	HJT Bifacial	HJT
No. of modules	8	8	8	8
String power (kW)	2.04 kW	2.24 kW	2.24 kW	2.56 kW
Date of Installation	6/14/2016	6/14/2016	6/14/2016	12/1/2016
Inverter	ABB PVI 3.0	ABB PVI 3.0	ABB PVI 3.6	ABB PVI 3.6
MPPT channel	Inv1 MPPT1	Inv2 MPPT1	Inv3 MPPT1	Inv4 MPPT1

Task 2: Construction

Modules were initially received from Silevo on 11/4/2015. Field installation of PV racking and initial module mounting occurred on 2/24/2016. Data acquisition for the system was initiated on 3/21/2016. System data was confirmed good with initial start-up errors fixed by June 2016. A fourth (final) set of modules (WR320) was received in the summer of 2016 and deployed outdoors and turned-on 10/19/2016.

SolarCity installation at NREL

The SolarCity RTC installation is composed of four strings of eight modules apiece, each connected to a grid-tied PV inverter. The four module types under test are: Trina TSM-255PA05.18, Silevo Triex H60-280 mono-facial, Silevo Triex H60 bifacial and Silevo W320-WR. Figure 1 shows the SolarCity installation at NREL, with a schematic view shown in Figure 2.

Figure 1: View of the SolarCity installation at NREL, with W320 modules in foreground.

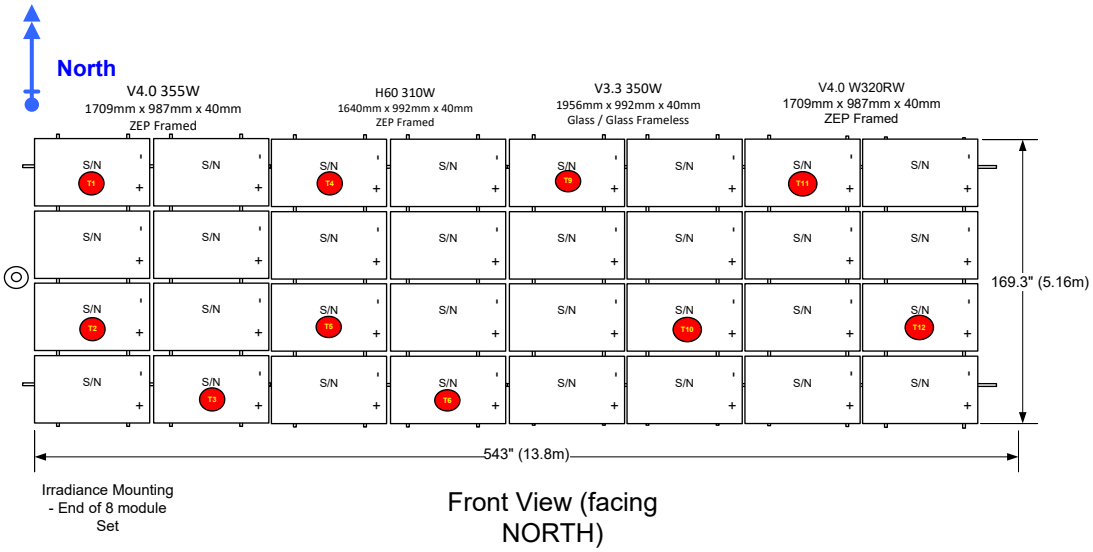

Figure 2: Module layout including mounting position of the forward-facing IMT reference cell, and module temperature measurements. Serial numbers are listed in the Appendix.

Task 3: Data Acquisition and Analysis
The main purpose of the Regional Test Center deployment was to collect performance data and issue reports to Silevo. Field data was collected for the remainder of the project, and six proprietary test reports issued:

- 201606 Initial Capacity Test Report
- 201701 NREL 6-month energy test report
- 201707 NREL 12 month energy test report
- 201803 NREL 18 month energy test report
- 201809 NREL 24 month energy test report
- 201907 NREL final (36 month) energy test report

The raw performance data is considered Protected CRADA Information. Below are excerpts from a non-protected summary of the test procedure and some findings are presented below to describe data for the completed tasks.

Energy analysis: IEC 61724-3

1. Test Boundary

IEC 61724-3 is clear to require a definition of test boundary—i.e. which elements of the installation are inside or outside of the region of analysis. The inputs are typically defined by external weather conditions including global horizontal irradiance, wind speed and ambient temperature. The system outputs are usually defined to be AC energy delivered to the grid. In this case, because we are mainly interested in PV module relative performance, we can reduce model uncertainty by defining a system boundary closer to the PV strings. In this case, back-of-module temperature is measured, and plane-of-array irradiance is measured with a matched IMT reference cell. Output power is measured at the DC string level too. Monitoring equipment is detailed in Appendix A.

Other environmental conditions are uncontrolled—including ground albedo, natural snow/soiling and nearby shade obstructions. These factors will be described below. For the first three PV strings, proper data collection started June 14, 2017. This date is chosen for the start of the energy analysis.

2. Data analysis

Production data is averaged over 1-minute intervals, and filtered only for irradiance and DC power > 0. Prior to filtering, data availability was assessed to be 88.3%—-a three-day outage for the H60 bifacial inverter was noted between July 3, 2016 and July 6, 2016, and again from July 2nd, 2017 to July 7th 2017. Additional data for the entire system was missing due to Ethernet outage at the site, and an improperly configured local backup. Due to these issues on NREL's end, a total of 930 hours of data are missing from the analysis interval, mainly in August and September 2016, and November 2017.

An additional 98-day forced outage was also logged between 10/4/2018 and 1/10/2019 due to an interconnect agreement dispute and re-negotiation with the site utility Xcel Energy. This was resolved by installing required production metering and updating research PV and Energy Storage assets at the NREL Regional Test Center campus site. This adds another 2350 hours of

lost data and system de-energized time (modules were at open circuit) to the experiment period under consideration.

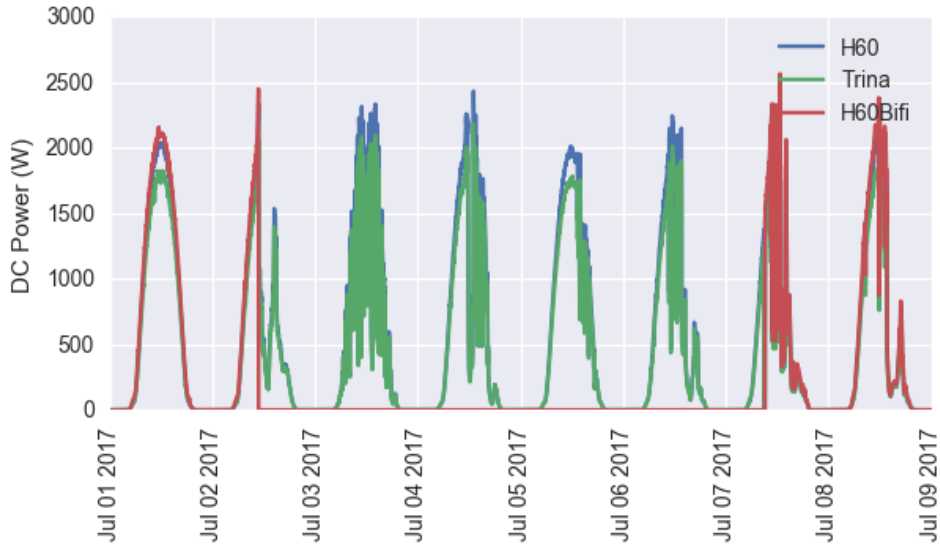

Figure 3: Data outage at the NREL SolarCity system only for H60 Bifacial string.

Monthly kWh production for each string is shown in Figure 4.

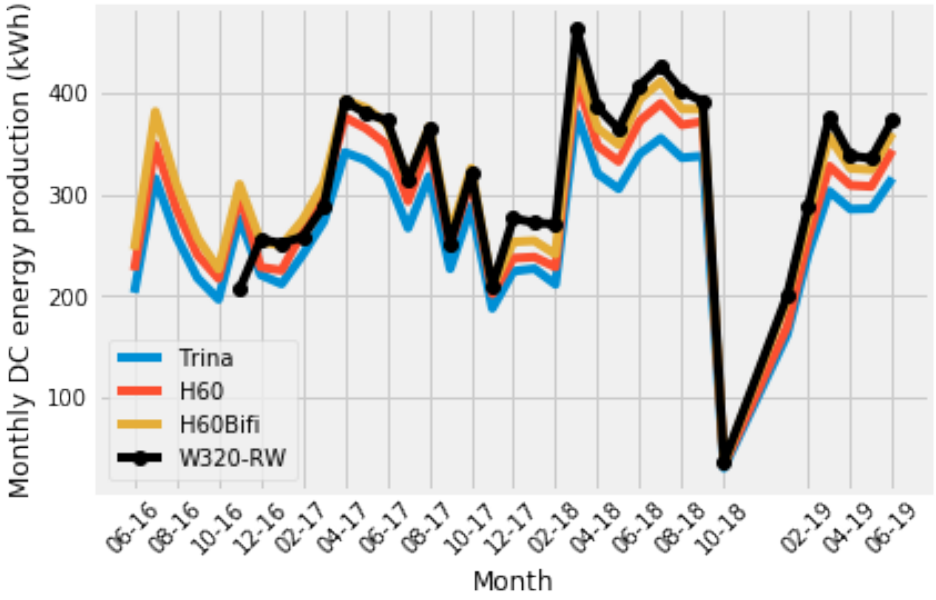

Figure 4: Monthly kWh production for the four SolarCity strings. June 2016 is a partial month for strings 1-3. November 2016 is a partial month for the W320-RW string. October 2018 – January 2019 are partial months.

Further Analysis of Bifacial modules

The main purpose of this test site is to evaluate the performance advantage of bifacial PV modules. We should first note that the field test site is not optimized for bifacial response. The ground below is relatively low—natural dirt and brush. Furthermore, although rear obstructions

from back-mounted inverters were minimized, there is likely to be rear shading from racking and structural cross-members. This being said, we can assess the bifacial gain in energy for each month of our deployment according to:

$$BG_E = 100\% * \left(\frac{\sum P_{bifacial}/P_{mp}}{\sum P_{monofacial}/P_{mp}} \right) \quad (3)$$

$$Bifaciality\ \varphi = \frac{P_{mp,rear}}{P_{mp,front}} \quad (4)$$

Here P_{mp} is the measured single-sided power of each string from factory flash data, not nameplate rating, in order to more carefully account for the direct benefit of bifacial production.

On a cumulative basis, the H60 bifacial module type produced 6.7% more energy than its monofacial peer (Figure 5). This was highest in the month of December and January, which experienced snow. In the context of the ability to capture available backside resource, this is approximately the same bifacial gain as expected, since the rear irradiance resource is on average only 6.9% of the front resource (Figure 6). This result is summarized in Table 2.

Table 2: Bifacial gain for H60 bifacial modules

	H60 Bifacial
Bifaciality φ (Eq. 4)	0.92
Grear / Gfront (Fig. 13)	6.9%
BG_E (expected)	106.3 %
BG_E (measured)	106.7 %

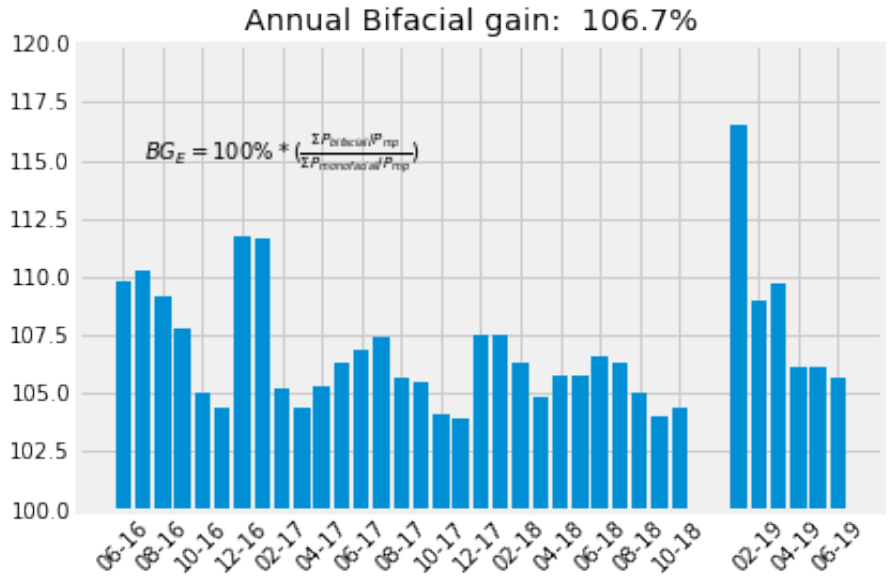

Figure 5: Bifacial energy gain for Silevo H60 bifacial modules deployed at the NREL RTC site.

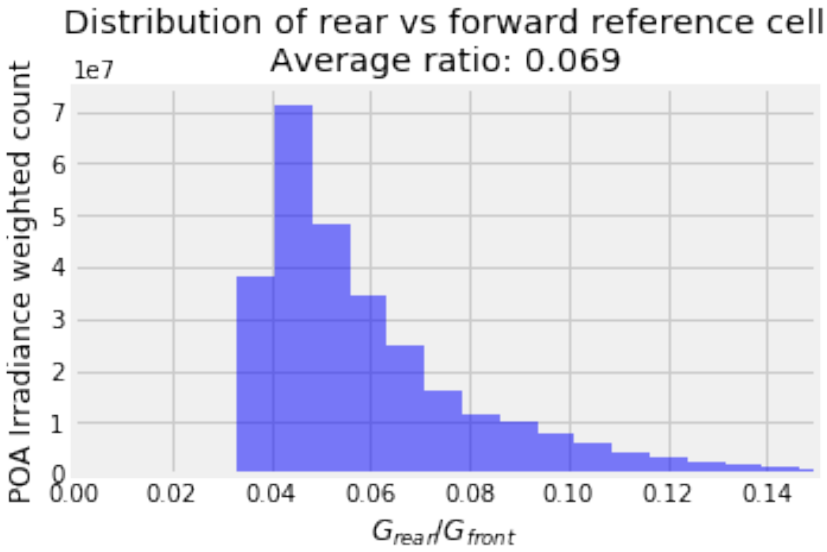

Figure 6: Distribution of G_{rear} / G_{front} weighted by POA irradiance as measured at the NREL site.

Bifacial performance is lower in June and July 2017-2018 relative to 2016, since the W320-WR modules were not in place prior to 11/11/16. Therefore, with the bifacial modules on the edge of a row, a somewhat higher unshaded field of view is visible to some of the modules, relative to the rear-facing reference cell deployed in the center of the bifacial modules. This edge effect has been shown to increase bifacial response in the morning. Now that we have installed the W320 modules to the east of the H60 bifacial modules, the AM response matches more closely to the PM response.

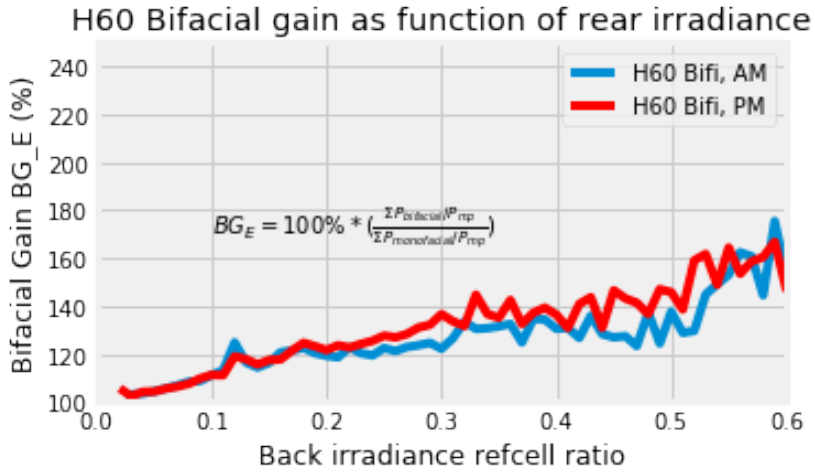

Figure 7: Bifacial gain as a function of rear-side irradiance. Morning and afternoon response is compared, showing comparable response now that WR320 modules have been installed.

Figure also shows that the measured bifacial gain of these modules increases with higher rear irradiance, therefore deploying these modules in a higher albedo environment will increase their bifacial energy production.

Task 4: Final Report

The final CRADA report deliverable comprises this document. The sponsor chose to waive decommissioning and to transfer ownership of the system to NREL.

Mod 1 Task:

This task was simply to add an equipment list to the CRADA document, which was completed.

Value to DOE, Partner and US Manufacturing:

DOE Mission Area to benefit from this CRADA:

Energy	**[X]**
Environmental Quality	**[ ]**
Science	**[ ]**
National Security	**[ ]**
Other, name	**[ ]**

CRADA benefit to DOE, Participant, and US Taxpayer:

_X__ *Assists laboratory in achieving programmatic scope,* _X__*adds new capability to the laboratory's core competencies,* _X___ *enhances the laboratory's core competencies,* ___ *uses the laboratory's core competencies, and/or* ____ *enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.*

Partner and US Manufacturing benefit:

The field test data collected through this CRADA provided valuable information and results that were partly responsible for the successful sale / acquisition of Silevo by SolarCity and finally Tesla, Inc. The intellectual property being investigated at this site was successfully transferred to industry and through collaboration with Panasonic, Inc is being deployed and manufactured at the Tesla Gigafactory 2 in Buffalo, NY. Tesla employs 800 people at their Gigafactory 2 as of November 2018.

Subject Inventions Listing:

None

ROI #:

None

Responsible Technical Contact at Alliance/NREL:

Chris Deline | chris.deline@nrel.gov

Name and Email Address of POC at Company:

Christoph Erben | cerben@tesla.com (Tesla acquired Silevo)

DOE Program Office:

Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office