SANDIA REPORT
SAND2023-03135
Unlimited Release
Printed May 2023

The 2021 Blind PVPMC Modeling Intercomparison

Marios Theristis, and Joshua S. Stein

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@osti.gov
Online ordering:	http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.gov
Online order:	https://classic.ntis.gov/help/order-methods/

ABSTRACT

This document provides the instructions for participating in the 2021 blind photovoltaic (PV) modeling intercomparison organized by the PV Performance Modeling Collaborative (PVPMC). It describes the system configurations, metadata, and other information necessary for the modeling exercise. The practical details of the validation datasets are also described. The datasets were published online in open access in April 2023, after completing the analysis of the results.

ACKNOWLEDGEMENTS

Sandia would like to thank the Technical University of Denmark (DTU) and Nicholas Riedel for supplying the PV system data from Roskilde.

This material is based upon work supported by the U. S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38267 and 38268.

CONTENTS

This page left blank

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
Gpoa	global irradiance on the plane-of-array
GHI	global horizontal irradiance
DNI	direct normal irradiance
DHI	diffuse horizontal irradiance
Tamb	ambient temperature
Tmod	module temperature
RH	relative humidity
WS	wind speed
SAPM	Sandia array performance model
IAM	incidence angle modifier
NMOT	nominal module operating temperature
PVPMC	PV performance modeling collaborative

1. OBJECTIVES

The objectives of this blind PV performance modeling intercomparison were to:

1. quantify differences among modelers
2. investigate whether some models are more accurate than others
3. see if performance modeling can be improved
4. quantify validity of PV performance models
5. find sources of uncertainty
6. develop workplan to improve functionality and reproducibility

2. SCENARIOS

Six scenarios of practical interest to the community were identified to include a) fixed and tracking systems, b) monofacial and bifacial modules, c) modules beyond the traditional aluminum back surface contact (Al-BSF) technology, d) distinctively different geographical locations/climates (see Table 1). The six scenarios include:

1) 3.9 kW of monofacial, fixed-tilt, Panasonic heterojunction with intrinsic thin layer (HIT) in Albuquerque, New Mexico over a 1-year period
2) 3.3 kW of monofacial, fixed-tilt, Canadian Solar mono-crystalline silicon (mono-c-Si) in Albuquerque, New Mexico over a 1-year period
3) 26.84 kW of monofacial, tracked, Trina mono-crystalline silicon passivated emitter and rear cell (PERC) in Roskilde, Denmark over a 1-year period
4) 25.96 kW of bifacial, tracked, Trina mono-crystalline silicon PERC in Roskilde, Denmark over a 1-year period
5) 26.84 kW of monofacial, fixed-tilt, Trina mono-crystalline silicon PERC in Roskilde, Denmark over a 1-year period
6) 25.96 kW of bifacial, fixed-tilt, Trina mono-crystalline silicon PERC in Roskilde, Denmark over a 1-year period

Table 1: Characteristics of the six scenarios used in this blind modeling intercomparison. These were selected to include a) fixed and tracking systems, b) monofacial and bifacial modules, c) modules representative of the current PV market and upcoming technologies, and d) distinctively different geographical locations/climates.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Site information						
Location	Albuquerque, New Mexico	Albuquerque, New Mexico	Roskilde, Denmark	Roskilde, Denmark	Roskilde, Denmark	Roskilde, Denmark
Latitude	35.05° N	35.05° N	55.696° N	55.696° N	55.696° N	55.696° N
Longitude	106.54° W	106.54° W	12.104° E	12.104° E	12.104° E	12.104° E
Altitude (m above sea level)	1600	1600	15	15	15	15
Time zone	MT (GMT-7)	MT (GMT-7)	CET (GMT+1)	CET (GMT+1)	CET (GMT+1)	CET (GMT+1)
System information						
Capacity (kW DC)	3.9	3.3	26.84	25.96	26.84	25.96
Inverter	SMA Sunny Tripower 20000TL-US	SMA Sunny Tripower 15000TL-US	Delta RPI M50A	Delta RPI M50A	Delta RPI M50A	Delta RPI M50A
Monofacial/ Bifacial	Monofacial	Monofacial	Monofacial	Bifacial	Monofacial	Bifacial
Technology	HIT	mono-c-Si	Mono-PERC	Mono-PERC	Mono-PERC	Mono-PERC
Manufacturer	Panasonic	Canadian Solar	Trina	Trina	Trina	Trina

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Model	VBHN325S A16	CS6K-275M 275W	Allmax+	Duomax Twin	Allmax+	Duomax Twin
Module nominal power	325 W	275 W	305 W	295 W	305 W	295 W
Fixed/Tracked	Fixed	Fixed	Tracked – horizontal single axis	Tracked – horizontal single axis	Fixed on a horizontal single axis tracker	Fixed on a horizontal single axis tracker
Tracking limit angle	N/A	N/A	±60°	±60°	N/A	N/A
Tilt Angle	35°	35°	Varies	Varies	25°	25°
Azimuth	180° (facing South)	180° (facing South)	90° or 270°	90° or 270°	180° ° (facing South)	180°° (facing South)
Back tracking	N/A	N/A	Yes	Yes	N/A	N/A
Tracker pitch	NA	NA	12 m ±0.1 m	12 m ±0.1 m	7.6 m ± 0.1 m	7.6 m ± 0.1 m
Hub height	NA	NA	1.95 m ±0.2 m	1.95 m ±0.2 m	2.3 m ± 0.1 m	2.3 m ± 0.1 m
Length			45.1 m	45.1 m	45.1 m	45.1 m
PV panel configuration	2-Up landscape	2-Up landscape	2V (2 Portrait)	2V (2 Portrait)	2V (2 Portrait)	2V (2 Portrait)
Total number of PV panels in system	12	12	88	88	88	88
PV panels in series	12	12	22	22	22	22
PV strings in parallel	1	1	4	4	4	4
Provided inputs [Albuquerque, Roskilde]						
Period	2020	2020	2019 - 2020	2019-2020	2019 - 2020	2019-2020
Resolution	Hourly averages reported at the end of the hour shown in the time column*	Hourly averages reported at the end of the hour shown in the time column*	Hourly averages reported at the end of the hour shown in the time column*	Hourly averages reported at the end of the hour shown in the time column*	Hourly averages reported at the end of the hour shown in the time column*	Hourly averages reported at the end of the hour shown in the time column*
Front Gpoa (W/m^2)	No	No	No	No	No	No
Rear Gpoa (W/m^2)	No	No	No	No	No	No

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
GHI (W/m^2)	Yes	Yes	Yes	Yes	Yes	Yes
DNI (W/m^2)	Yes	Yes	Yes	Yes	Yes	Yes
DHI (W/m^2)	Yes	Yes	Yes	Yes	Yes	Yes
Tamb (°C)	Yes	Yes	Yes	Yes	Yes	Yes
Tmod (°C)	No	No	No	No	No	No
RH (%)	Yes	Yes	Yes	Yes	Yes	Yes
WS (m/s)	Yes	Yes	Yes	Yes	Yes	Yes
Albedo	Yes (monthly averages in second tab of meteo data)	Yes (monthly averages in second tab of meteo data)	Yes (monthly averages in second tab of meteo data)	Yes (monthly averages in second tab of meteo data)	Yes (monthly averages in second tab of meteo data)	Yes (monthly averages in second tab of meteo data)
Availability of additional information						
Module spec sheet available	Yes	Yes	Yes	Yes	Yes	Yes
IEC 61853 matrix data available	Yes	Yes	No	No	No	No
SAPM coefficients available	No	No	No	No	No	No
PAN file available	Yes	Yes	No	No	No	No
IAM+NMOT report available	Yes	Yes	No	No	No	No

* e.g., 2 pm corresponds to the mean values measured between 1:01 pm and 2 pm. It is important when calculating solar positions; common practice is to shift the index 30-min back.

3. METHODOLOGY

In order to participate in this exercise one had to "copy and paste" their hourly estimates (i.e., POA irradiance, module temperature, DC power) into the corresponding tabs (S1 – S6) of the Results.xlsx file. Running all scenarios was optional, but strongly encouraged. In addition to the estimated hourly timeseries, the participants were requested to provide answers with respect to the model/software they used and inputs/assumptions according to the questionnaires at each excel tab.

Modeling results were due by September 10, 2021. All questions about the exercise were emailed to Sandia and then answered publicly in a Frequently Asked Questions section on the PVPMC website (copied in this report; see Section 6).

The results were collected and handled by Sandia. Sandia presented an anonymized summary of the results at the 2022 PVPMC workshop in Salt Lake City and also in a plenary talk in the 8th World Conference on Photovoltaic Energy Conversion, in Milan. Following these presentations, Sandia prepared a journal article [1] describing the study with all of the participants included as co-authors. The participants had the option to exclude their name.

4. DATA PROCESSING

Albuquerque input data are filtered according to the following conditions:

- GHI is higher than 0 and less than 1300 W/m^2
- DNI is higher than 0 and less than 1200 W/m^2
- DHI is higher than 0 and less than 800 W/m^2
- Wind Speed is higher than 0 and less than 32 m/s
- Relative Humidity is higher than 0 and less than 100%
- Albedo is higher than 0.15 and less than 0.25

Roskilde input data are filtered according to the following conditions:

- Solar elevation >5° above the horizon
- Tracker tilt angles for S3 & S4 matching within 5°
- All data acquisition systems available
- No morning shade present on tracker for S4

Night-time and instances of sensor outages are displayed as "zero" values; these datapoints were not considered in the PVPMC study [1]. In addition to the filters shown in the rightmost columns of S1-S6, the following conditions were also filtered out:

1) Front plane-of-array irradiance < 100 W/m^2
2) DC output power < 50 W
3) Ambient temperatures < -5°C and > 45°C

The year of 2020 was a leap year, but the datasets were filtered in a way to represent a TMY-like format with 8760 hours (i.e., excluding data collected on February 29, 2020). The hourly averages are reported at the end of the hour.

The datasets from the Technical University of Denmark (i.e., S3-S6) are also available through the following link:
https://data.dtu.dk/articles/dataset/Data_used_in_Validation_of_Bifacial_Photovoltaic_Simulation_Software_against_Monitoring_Data_from_Large-Scale_Single-Axis_Trackers_and_Fixed_Tilt_Systems_in_Denmark_/13580759/3

These are described in detail in the publication by N. Riedel-Lyngskær et al. [2].

5. PRACTICAL DETAILS

5.1. File structure

The datasets for all scenarios are available in an MS-Excel file. This file consists of seven sheets: one for general notes, and one for each scenario. Test reports, IEC61853-1 matrix data, PAN files, spec sheets, one-line diagrams, etc. are also included in the resources.

5.2. Download locations

The validation datasets are available online in open access at two locations. The first is on the website of the PV Performance Modeling Collaborative at https://pvpmc.sandia.gov/. The second is on the

Duramat Data Hub at https://datahub.duramat.org/dataset/pv-performance-modeling-data (doi: https://doi.org/10.21948/1970772) [3].

6. FREQUENTLY ASKED QUESTIONS

The following questions were received and answered during the exercise.

1. Is this model comparison only on the DC side, or does it include inverter capacity?
   - The blind modeling comparison is for DC power only.
2. What soiling loss values should be assumed?
   - Generally, both Albuquerque and Roskilde observe very low soiling rates. We would like to see how soiling assumptions vary among modelers, so we prefer not to give any values out. Therefore, you can assume any reasonable value of soiling that you think is more appropriate for these low soiling locations.
3. Are the strings always maintained at MPP?
   - Yes
4. What is the actual DC: AC ratio to be assumed? For example, for Albuquerque: A 3.9kW DC array is connected to a 20kW inverter. This would lead to higher inverter losses than useful
   - The 3.9 kW and 3.3 kW are single strings from separate systems which consist of 4 strings each. Each inverter has 2 inputs/MPPTs, therefore, 2 strings are placed on one MPPT input. The inverters were oversized to avoid any clipping. For example, the Panasonic system (15.6 kW for 4 strings) is connected to a 20.4 kW inverter (DC/AC ratio of 0.76) and the Canadian 275 system (13.2 kW for 4 strings) is connected to a 15.3 kW inverter (DC/AC ratio of 0.86). The Roskilde systems are connected to 50 kW inverters, which also have 2 MPPTs. Based on the frontside rating and rated inverter power, the DC/AC ratios in Roskilde are 1.04 (bifacial systems) and 1.07 (monofacial systems). However, the inverter has a max power input of 58 kW before clipping (see datasheet)
5. Is the weather data for the year 2020?
   - Yes, in Albuquerque. Roskilde is 2019-2020
6. Why is the weather file missing Feb 29th?
   - In order to avoid leap year effects, Feb 29th was removed. We also wanted to have a TMY compatible format with 8760 hours in a year.
7. What is the commissioning date for each array? There seem to be older modules installed and without any assumptions on degradation especially on the TRINA and PANASONIC modules it might lead to a gap in results.
   - The Canadian 275 system was commissioned in October 2017, whereas Panasonic was commissioned in June 2018. The systems in Roskilde were commissioned in August 2018.
8. What LID assumptions can be made?
   - The modules were exposed for 2-3 years prior to the year we shared. The modules with IEC 61853 data were also pre-conditioned according to the standard. The modelers can assume any LID values they feel are appropriate.
9. Are the U0 and U1 coefficients in CFV report for NOCT equal to U_c and U_v in PV Syst/Plant Predict?
   - No, these coefficients are for the Faiman model.
10. Are more specific inverter files or datasheets available?

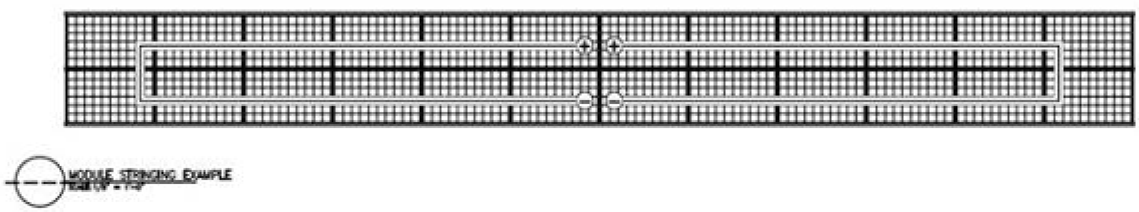
  - Yes, inverter datasheets have been uploaded for Albuquerque and Roskilde sites (see Files section above).

11. Can the IEC 61853 results be made available in xls format? Otherwise you'll have typos distorting the results.
    - The IEC 61853-1 matrix data are available in an excel file. It has been added above to the Files section.
12. Could you provide weather in one or five-minute intervals?
    - We are planning to include datasets of finer resolution in the next modeling comparison.
13. Could you provide photographs of the systems?
    - Photo of the Canadian Solar system in Albuquerque can be seen here. The Panasonic system is located on an identical rack in the same array field.
14. What is the row spacing for the fixed tilt sites?
    - The row spacing is 4.88 meters in Albuquerque and 7.6 meters in Roskilde. Row spacing is the distance between two identical positions in adjacent rows.
15. Could you provide layout information for shading calculations?
    - The modules are placed in a 2-up landscape configuration with a row spacing of 4.88 meters and 7.6 meters in Albuquerque and Roskilde, respectively.
16. Could you provide electrical layout for mismatch calculations?
    - Yes, figure below shows the stringing configuration of the modules in the arrays in Albuquerque.
17. Which of the data sources provided (spec sheet, matrix, PAN file) best represent the installed modules?
    - We provided all the information we have available in this modeling comparison. Some of the objectives are to see if any data sources are more preferrable than others and to investigate whether different data sources affect modeling accuracy or not. It is up to each modeler to decide which data source(s) is/are more appropriate. Modelers are welcome to send multiple results with different inputs given that they specify the differences in the questionnaires.
18. Please can you provide string (electrical) layout for Roskilde systems (or is it the same pattern as in Albuquerque)?
    - Each T6, T7, T12 and T15 subsystem from the Roskilde aerial photo consists of 4 strings of 22 modules. The 22 modules are connected in series in each string, and the 4 strings are in parallel. An example of the stringing configuration in Roskilde is shown below.
19. Can you provide the coordinates of the weather station in Albuquerque?
    - The location of the weather station: 35.0546°, -106.540105°.
20. I wanted to ask if there will be .PAN files provided for the Trina modules for cases 3 through 6?
    - Unfortunately, we do not have PAN files for the Trina modules but they might be available in the PVSyst database if you have access to it.
21. Can you provide single line diagrams?
    - Both Panasonic and Canadian Solar systems are connected in the same manner in Albuquerque, NM. Please note that only one string per system is modeled for the Albuquerque site (e.g., CM1 in the diagram below). The one-line for Albuquerque systems is here. The one-line for Roskilde is here.
22. Can you provide inverter OND files?

    - Unfortunately, we do not have any OND files for the inverters, but they might be available in the PVSyst database if you have access to it.

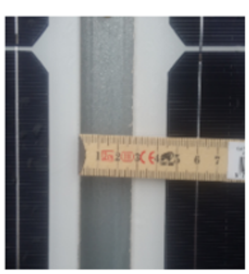
23. Can you provide fixed racking and HAST design drawing: we would like to build system 3D model and determine accurate shading factor and mismatch loss by ray-tracing method.
    - The following fixed racking and HSAT information are available for the Roskilde site which equips the bifacial modules.
24. Are you asking for POA irradiance or *effective* POA irradiance?
    - We are looking for POA irradiance. Your calculated POA irradiance values will be compared against pyranometer data.

- Albuquerque Figures:



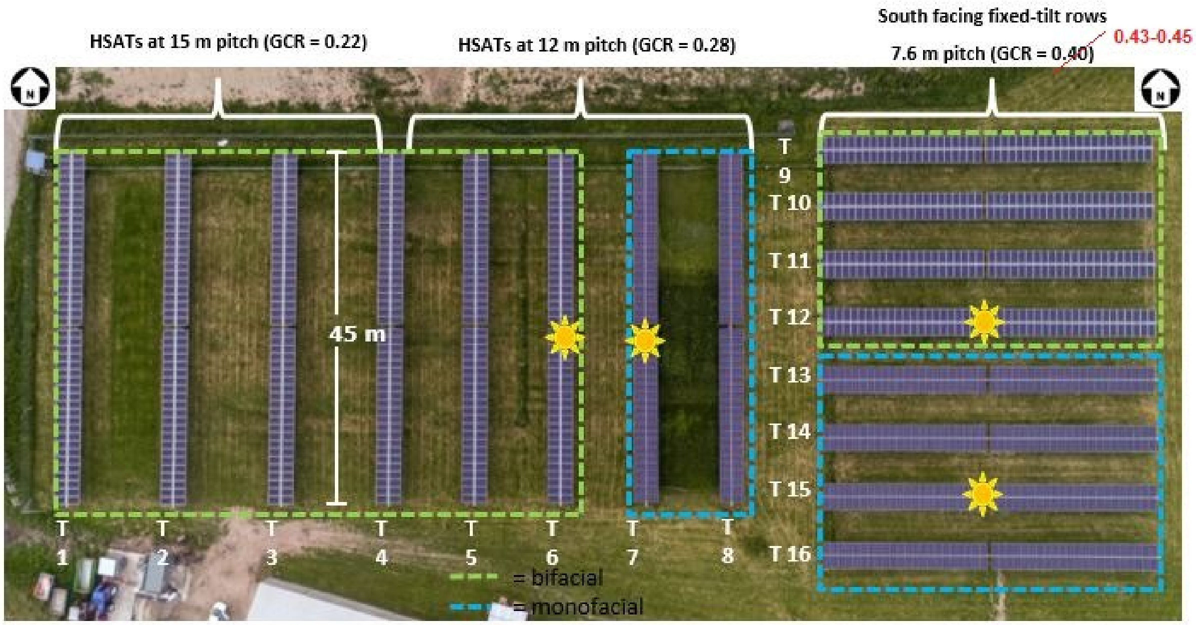
- Roskilde Figures:

Item	Single Axis Tracker	Fixed Tilt	Notes
Manufacturer	SolTec	SolTec	
Model	SF7	SF7	
Tracking limit angle / Tilt angle	± 60°	25°	Fixed tilt units have been oriented south and do not track the sun
Azimuth	90° or 270°	180°	Trackers face 90° (East) before solar noon and 270° (West) after
Back tracking	Yes	NA	
Tracker pitch	12 m ±0.1 m	7.6 m ± 0.1 m	
Hub height	1.95 m ±0.2 m	2.3 m ± 0.1 m	
Length	45.1 m		
PV panel configuration	2V (2 Portrait)		
PV panels per structure	88		
PV panels in series	22		
PV strings in parallel	4		
Torque tube gap between 2V modules	14.5 cm		
Torque tube dimensions	14.5 cm x 14.5 cm		
Torque tube distance from PV backside	11.5 cm		

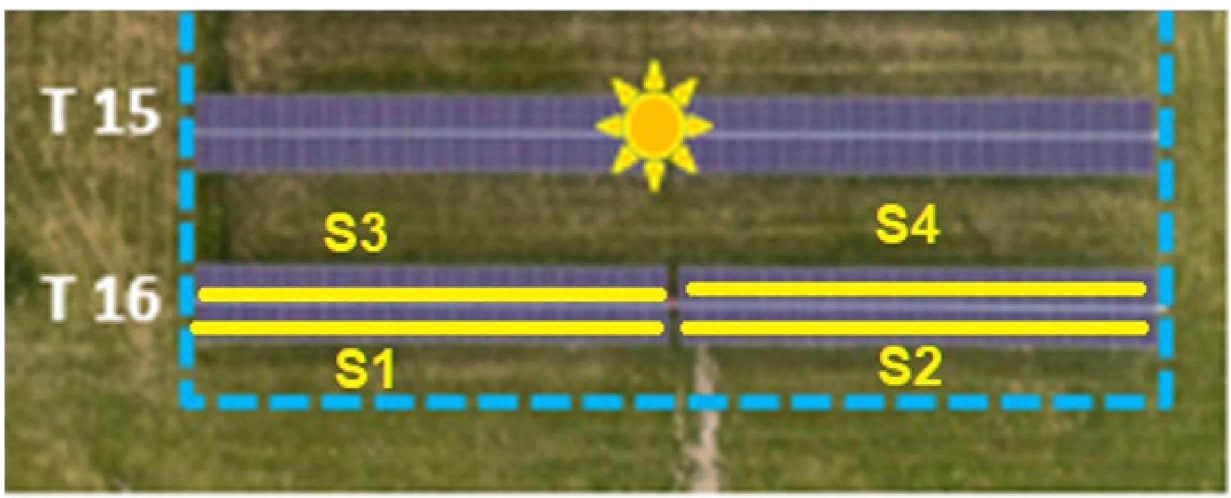

Al mounting rails between panels (spacing ~2.7cm)


Torque tube gap ~14.5 cm


Tracker motor gap ~0.5 m



The subsystems to model are T6, T7, T12,and T15 (indicated with the sun symbol)



REFERENCES

[1] M. Theristis, " Blind photovoltaic modeling intercomparison: a multidimensional data analysis and lessons learned," in preparation, 2023.

[2] N. Riedel-Lyngskær et al., "Validation of bifacial photovoltaic simulation software against monitoring data from large-scale single-axis trackers and fixed tilt systems in Denmark," Applied Sciences, vol. 10, p. 8487, 2020.

[3] M. Theristis and J. S. Stein, "PV Performance Modeling - Data and Resources, " in DuraMat Data Hub https://doi.org/10.21948/1970772, accessed in April 24, 2023.

DISTRIBUTION

Email—Internal

Name	Org.	Sandia Email Address
Technical Library	01977	sanddocs@sandia.gov

This page left blank