Modeling and Production Performance Analysis of a Campus 5MW Solar Installation in the California San Joaquin Valley

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Abstract

A production analysis of a utility-scale solar system is presented in this paper. This system is installed as parking lot shade structures with a 7° tilt on a small urban university campus. It is comprised of 12,780 panels arranged in 45 arrays over eight locations for a total of 5.35 megawatts DC of capacity. The arrays have different orientations with most in a south-southeast (162° azimuth) and a west-southwest (252° azimuth) orientation. Theoretical system performance was determined using a variety of models available in the open-source pvlib python package (Anderson, 2023; Holmgren, 2018) and compared to a simple irradiance-based effective efficiency model. The theoretical performance is validated using onsite weather and solar irradiance measurements. Comparisons of theoretical, measured, and system performance characteristics are presented in this paper. Knowing real system performance comparisons to projected performance is an important component of closing the loop to improve system modeling and design.

Introduction

In May 2022, the University of the Pacific commissioned a 5.35 MW (DC) photovoltaic power system, with specifications as shown in Table 1. The system was designed to meet approximately 30% of the campus' energy generation needs, making the system the largest in on-campus generation among private universities at the time of installation. In this work, we present a preliminary analysis of the system bymodeling one of the subsystems – the arrays of parking Lot 4, also specified in Table 1. In this modeling, the clear-sky daily production is compared to the actual production of the sub-system during a summer day, June 21, 2023 (summer solstice), and a winter day, December 16, 2023 (the nearest clear day to winter solstice).

To comply with California Public Utilities Code for Renewable Energy Self-Generation Bill Credit Transfer (RES-BCT), the system's AC output was derated to 4.06 MW from 4.44 kW (Baird, 2008). This was accomplished by derating the inverters to a maximum output of 36.6 kW each. This effectively increases the system's overload ratio and creates many days of significant clipping. Inverter overloading is a common practice to maximize a systems output over the course of a year. It can be calculated by:

$$Overload\ Ratio = \frac{Array\ Power\ [W]}{Inverter\ Power\ [W]}$$

Clipping occurs when the power generated by an array exceeds the power capacity of the inverter. When a system is designed with an overload, this often occurs on peak summer days.

Table 1. University of the Pacific's PV system parameters.

Item	Total System	Lot 4 (Canopy 1)	Lot 4 (Canopy 2)	Lot 4 (Canopy 3)
No. of Modules	12780	444	444	504

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No. of Inverters	111	4	4	4
Strings/Inverter	n/a	18.5	18.5	18
Azimuth	varies		162°	
Tilt	7°			
Overload Ratio	1.25 (avg)	1.18	1.18	1.34
Module Ratings	415/425 W		425W	
Inverter Ratings	40 kW (derated to 36.6kW)			

Methods

Two different models were used to predict the system output – a simple irradiance-based effective efficiency model (IBEEM) and the standard models in pvlib python package (Anderson, 2023; Holmgren, 2018). The simple IBEEM model is now described.

The AC power output is given as:

$$P_{AC} = \begin{cases} \lambda \cdot P_{DC} \\ P_{AC,max} \end{cases}$$

λ is the nominal conversion efficiency of the inverters. If the AC power calculated using conversion efficiency exceeds the maximum power rating of the inverter, the inverter is saturated and the output power is capped.

The DC power is predicted by multiplying the measured plane of array (POA) irradiance, G_{irr} [W/m^2], the system's effective efficiency, η_{eff}, the single module panel area, A_p [m^2], and the number of modules, N_M:

$$P_{DC} = \eta_{eff} \cdot G_{irr} \cdot A_p \cdot N_M$$

The effective efficiency considers the power-based age and temperature effects, as described in the module datasheet. Effective efficiency is calculated by:

$$\eta_{eff} = \eta_0[1 + (T_{BOM} - 25)\gamma][\alpha_0 + (t - 1)\alpha_P]$$

η_0 is the module conversion efficiency, T is the back-of-module temperature, γ is the temperature degradation coefficient, α_0 is the year 1 degradation, t is the module/system age, and α_P is the power degradation coefficient.

Data for this model is provided by the on-site solar resource monitoring equipment shown in Figure 1. The solar resource monitoring equipment consists of three EKO MS-80 Class A pyranometers arranged in two plane-of-array orientations (162° and 252° at 7° tilt) and a global horizontal orientation; a back-of-module temperature sensor; and

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weather sensors for temperature, humidity, barometric pressure, wind speed and direction.

Fig. 1. Solar irradiance and weather monitoring station co-located in University of the Pacific's parking lot 4.

The pvlib python modeling parameters are summarized in Table 2. As described in Table 1, the Lot 4 arrays create three shade canopies and are connected to 12 inverters. The size of two of the canopies is identical. To compute the total production of the Lot 4 sub-system, the single array outputs are multiplied by the corresponding number of inverters:

$$P_{AC,total} = 8P_{AC0} + 4P_{AC1}$$

P_{AC0} is the AC power produced by an array of 18.5 modules x 6 strings connected to an inverter, and P_{AC1} is the AC power produced by an array of 18 modules x 7 strings connected to an inverter.

Table 2. pvlib-python modeling parameters for the Lot 4 sub-system array.

Parameter/Method	Value
Latitude	37.98
Longitude	-121.31
Time Zone	GMT+8
Surface Tilt	7
Azimuth	162
Modules Database	CEC
Inverter Database	CEC
Mounting	Fixed

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Temperature Models	sapm, open rack glass/glass
Shading	0
AOI Model	physical
Spectral Model	no loss
GHI/DNI/DHI	clearsky

Results

Both the IBEEM and pvlib python models require irradiance data to predict the system production. To verify the summer (July 1) and winter (Dec 16) days are clear-sky days, the predicted clear-sky (from pvlib python) and measured global (GHI) and plane-of-array (POA) irradiance were compared for two days that represent typical near-peak summer and winter. Results show excellent agreement as shown in Figure 2.

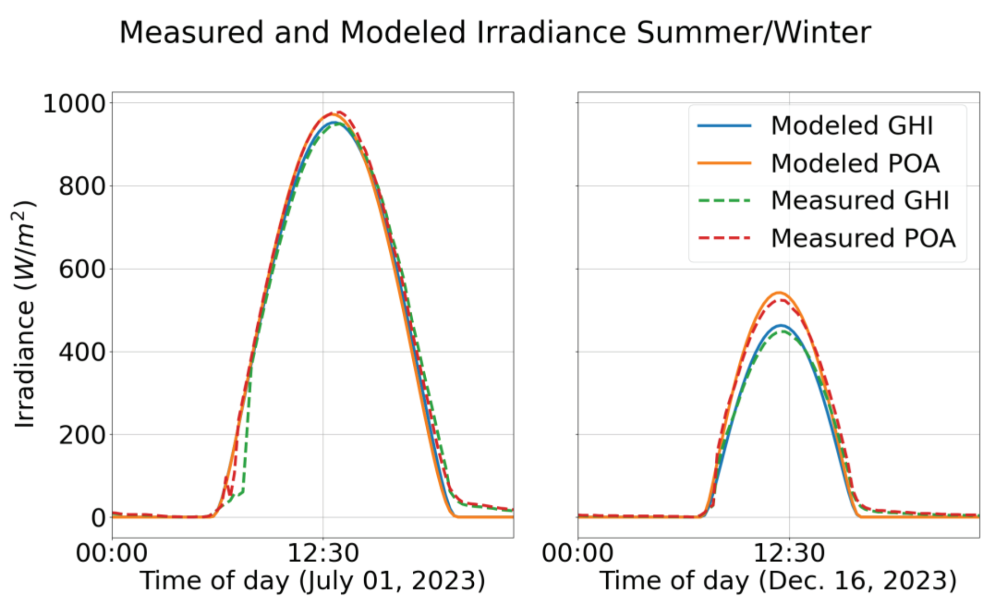

Fig. 2. GHI and POA clear-sky irradiance.

Figure 3 shows the predicted from both IBEEM and pvlib and the actual measured AC power production numbers for the parking lot 4 subsystem arrays.

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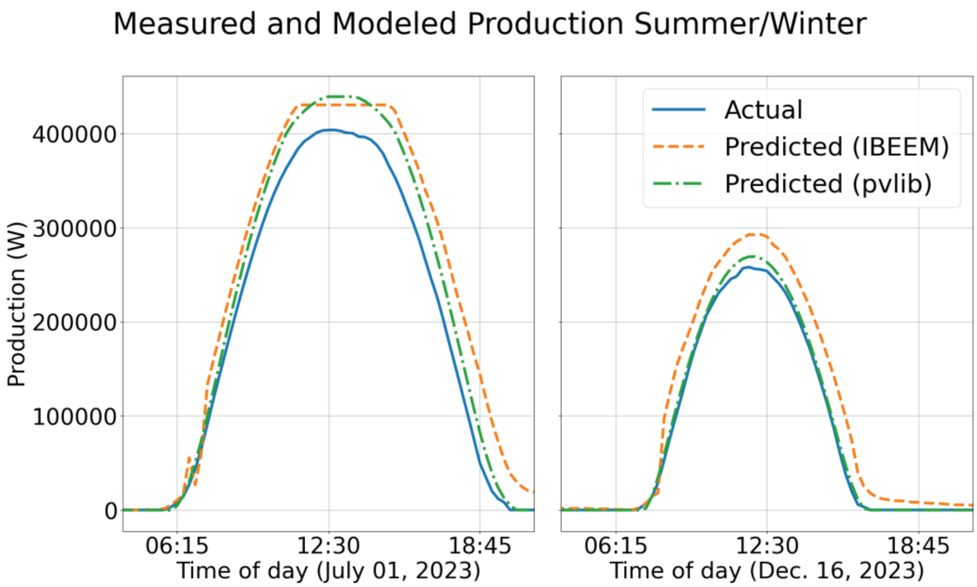

Fig. 3. Predicted and Actual Lot 4 System Production.

For the winter day, the pvlib model has excellent agreement with the actual production, with a slight overestimation during the peak of the day. This overestimation agrees with the slightly less-than-ideal irradiance conditions during peak day as shown in Fig. 2. For the summer day, the pvlib model overestimates the production significantly. For both predictions, show the system output clipping due to the inverter capacity. The actual production also indicates inverter clipping, but at a lower level than expected. This is likely due to both models not being able to fully account for the inverter efficiency reductions due to the heating effects of having to dissipate the excess energy.

Conclusions

In this work, the production of a set of arrays, representing a subsystem, was analyzed and modeled for a 5.35-MW (DC) campus system set up as parking canopy shade structures. Since this system has inverters that are artificially capped at a lower power level to comply with non-utility production limits, these inverters are subject to additional stress to dissipate this extra power. This presents some unique circumstances that will require additional modeling considerations to accurately represent the actual system production. While the pvlib model was acceptably accurate for the winter modeling, where no inverter clipping was present, the model was not as accurate during the summer day. Future work will focus on determining how this overloading can be modeled and how this affects the long-term durability of the inverters.

Conflict of Interest

This work was supported by a strategic investment grant from the School of Engineering and Computer Science at the University of the Pacific. System-level information and data were kindly provided by the Office of Sustainability at the University of the Pacific.

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