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Modeling Heat Dissipation in Earth Mount Solar™ PV Technology

White Paper

Abstract

This paper addresses the unique attributes of an Earth Mount Solar® PV system and its recommended treatment within PVsyst modeling software. PVsyst is a simulation software program that enables the user to model the expected thermal performance of their solar installation in order to accurately estimate production. It is the most widely used such program in the industry today. However, it was developed with elevated fixed-tilt and tracker systems in mind and therefore does not sufficiently consider the ground-based, heat-sink effect that the soil imparts on the thermal performance of Earth Mount Solar™ systems, which are installed directly on the ground.

This paper details a solution to this problem — a concept called Apparent U_C — that enables users of PVsyst to accurately represent this missing geothermic variable and better predict the expected energy production values of an Earth Mount Solar® PV system. This solution was endorsed by DNV, an independent third-party engineering firm that conducted a thorough technological assessment of Earth Mount Solar® PV, including close analysis of real-world data generated at an Earth Mount Solar® PV project site over a period of five months. This analysis led DNV to recommend an Apparent U_C value for PVsyst of 18.5 W/m2K.

Using DNV's recommended Apparent U_C value of 18.5, PVsyst modeling showed that Earth Mount Solar® PV arrays perform comfortably within accepted industry parameters for heat dissipation and overall energy performance.

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Modeling the Thermal Performance of Solar Modules

Standard Heat Dissipation Modeling

In order to accurately predict the performance of photovoltaic (PV) power plants, it is necessary to first understand how the solar modules in your specific project will dissipate heat during operation. It is not enough to understand the thermal performance of solar modules generally. There are numerous factors — including installation method, module construction, wind patterns, and others — that affect how much heat is dissipated by a module, and the impact of each of these factors on thermal performance can be different from project to project.

Because of its widespread acceptance and use within the solar industry, we chose to use PVsyst to model the thermal performance of the Earth Mount Solar® PV installation at the Bear Mountain site in Kern County, California. This approach allows for the most accurate baseline comparisons to be made between Earth Mount Solar systems and the most common traditional system types in use today.

The PVsyst model of heat transfer is as follows:

$$T_{cell} = T_{amb} + \frac{1}{U} * (\alpha * G_{inc} * (1 - \eta_{mod}))$$

Here, T_{cell} is the module operating temperature, $T_{\_amb}$ represents ambient temperature, α (or Alpha) is the absorption coefficient of solar radiation, $G_{\_inc}$ is the amount of radiance hitting the PV plane, and η_{mod} is the efficiency of the module according to operating conditions.

To calculate the U-value, which represents the overall heat dissipation factor, PVsyst uses the following equation:

$$U = U_c + U_v * v_{wind}$$

Here, U_c is the amount of heat dissipation constant to the module, U_V is the amount of heat dissipation due to wind, and v_{wind} is the wind velocity.

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These equations aren't perfect and lack predictive accuracy when assessing a wide variety of installation methods. As noted on PVsyst's website, "The determination of the parameters U_C and U_V is indeed a big question. We have some reliable measured data for free mounted arrays, but there is a severe lack of information when the modules are integrated."[1]

The same lack of information applies to modules installed directly on the ground, which introduces heat transfer dynamics that are quite different from those seen in building-integrated systems: whereas the roof or wall of a building is insulative, blocking the free flow of air around the module as well as trapping heat, the earth acts as a heat sink, drawing heat away from the underside of the Earth Mount Solar® PV array and cooling the system.

Because PVsyst uses only two heat dissipation terms, it is unable to natively account for this radiative heat transfer from an Earth Mount Solar® PV array to the underlying earth. According to a report published by Sandia National Laboratories, failure to model the heat dissipation of modules "relative to their mounting configuration" can lead to heat dissipation predictions that are off by 10% or more.[2]

These shortcomings are understandable. Until recently, it has not been common or practical to install modules directly on the ground. As a result, there has been no industry need for equations that accurately capture the heat dissipation properties of such systems.

That has now changed with the introduction of Earth Mount Solar® PV. While we fully expect future versions of PVsyst to better account for radiative factors, especially given the transformative potential of solar arrays installed directly on the ground, a revised model is needed in the meantime that enables more accurate heat dissipation and energy yield predictions in such systems. As a solution, we have utilized what we call Apparent U_C — a concept explained in more detail in the following section.

Using Apparent U_c as a Substitute for U_g

The PVsyst model includes only two editable U-terms: U_C (the amount of constant heat dissipation) and U_V (the amount of heat dissipation due to wind). It is not possible to manipulate the U-total data within PVsyst. However, to accurately predict

Cited References

1. Array Thermal Losses (Link)
2. PV Performance Modeling Workshop Summary Report (Link)

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heat dissipation and overall thermal performance in an Earth Mount Solar® PV system, we require a third term ("U_g") that represents the heat-sink effect of the ground upon the modules.

Since this term is not currently offered within PVsyst's model, we employed a workaround, endorsed by DNV in their technological assessment report of the Earth Mount Solar® PV installation at Bear Mountain, that we call Apparent U_c — a substitution of the standalone U_c variable used in PVsyst with a more comprehensive version that combines U_c and U_g. This allows us to better account for the earth's heat sink effect and quantify its impact on the thermal performance of the modules resting upon it.

DNV agreed with this approach and recommended using a thermal coefficient (or Apparent U_c) of 18.5 W/m2K. This figure was based on their review of the ambient and back-of-module temperature data generated at the site, their recognition of the need for a geothermal coefficient derived from measured soil temperature, and an assumption of no wind dependence ($U_v = 0$) since the modules sit on the ground. We adopted the DNV recommendation to use 18.5 as our Apparent U_c term, which provided energy modeling outcomes that aligned with (and in fact slightly underperformed) the real-world Bear Mountain data. We recommend reading the full DNV report for more details on this specific point, but the general takeaway is this: by using an Apparent U_c value of 18.5 W/m2K in PVsyst, we can generate Earth Mount Solar® PV energy predictions that are "well within the typical uncertainty of standard energy estimates."[3]

Heat Dissipation and Energy Yield in Traditional Solar Installations

The typical heat dissipation values for the most common traditional solar installation types are shown in Figure 1 below, not including Earth Mount Solar® PV.[4] To provide for easier comparison of these systems, we have added what we call an "energy yield factor," which predicts the expected annual energy yield (MWh/year) of a given system type in relation to the expected annual energy yield of flush rooftop PV. A system that has an energy yield factor of 1.13, for example, can be expected to produce 13% more energy over the course of a year than a standard flush rooftop PV system.

Cited References

3. Technology Assessment, Earth Mount Solar™ PV system (DNV Bankability Report)

4. Assessing the Outdoor Operating Temperature of Photovoltaic Modules (Link)

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PV Mounting Type	Heat Dissipation Values (U=W/m^{2}K)	Energy Yield per 2MW Array
Flush Rootop PV (fully insulated backside)	U=15.5 Uc=15 Uv=0.5	4,580 MWh/year at DC:AC =1.44 Energy Yield Factor = 1
Ballasted C&I Rooftop PV w/ Tilt (partially insulated backside)	U=20.5 Uc=20 Uv=0.5	5,190 MWhr/year at DC:AC=1.44 Energy Yield Factor = 1.13
Fixed-Tilt and Tracker PV (open-air backside)	U=29 Uc=27 Uv=1.2	5,853 MWhr/year at DC:AC=1.33 Energy Yield Factor = 1.28

Figure 1 — Heat dissipation values and energy yield of common mounting configurations

These heat dissipation and energy yield values represent the range of thermal performance outcomes considered acceptable in the industry today, as each of these system types is commonly used across the world. In the next section, we share our data from the Earth Mount Solar® PV installation at Bear Mountain and compare the values found there with the values identified above. As you will see, Earth Mount Solar® PV compares favorably to these systems and sits comfortably within the industry's established thermal performance expectations.

Modeling Heat Dissipation in Earth Mount Solar® PV

The Bear Mountain Project Site

In August 2021, the installation of a 274kWdc Earth Mount Solar® PV array was completed in Bakersfield, California — known as Bear Mountain. We have since gathered robust datasets from the Bear Mountain site, which consists of 720 380W solar modules and four 50kWac inverters. We have thoroughly analyzed these datasets, performed further regression calculations to determine the Bear Mountain array's baseline U-heat dissipation rates and back-of-module temperature fluctuations, and asked DNV to provide an independent, third-party validation of our approach, assumptions, and results, which they did as part of a broader technological assessment report on the Earth Mount Solar® PV system.

Data Collection at Bear Mountain

In order to demonstrate the extent to which the ground acts as a heat sink upon Earth Mount Solar® PV modules, it was necessary to measure back-of-module temperatures at Bear Mountain at sub-hourly intervals across multiple seasons. This was done with silver, epoxy-mounted resistance temperature detectors, which captured back-of-module temperatures every five minutes from August 6, 2021 through January 22, 2022. When looking at the raw unit regression for the full five-month dataset (Figure 2), we observed 22.8 W/m2K of total power or heat dissipation prior to accounting for the time of day that each data point was recorded.

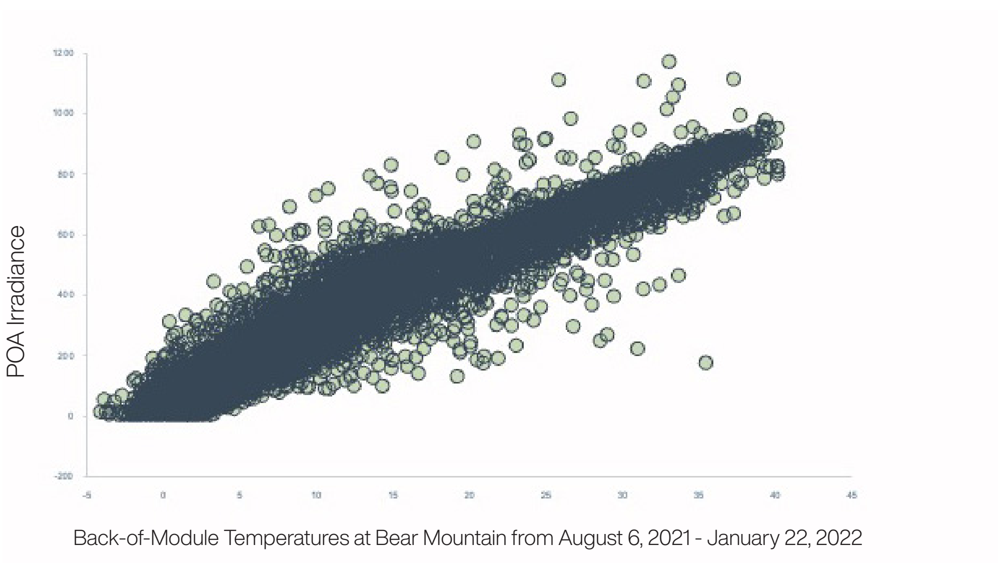

Figure 2 — Full five-month dataset of total heat dissipation at Bear Mountain

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DNV then took the raw information shown in Figure 2 and plotted each data point by the hour of day at which it was recorded. The resulting scatterplot is shown in Figure 3 below, where the relationship between time of day and the value of U_C becomes more apparent.

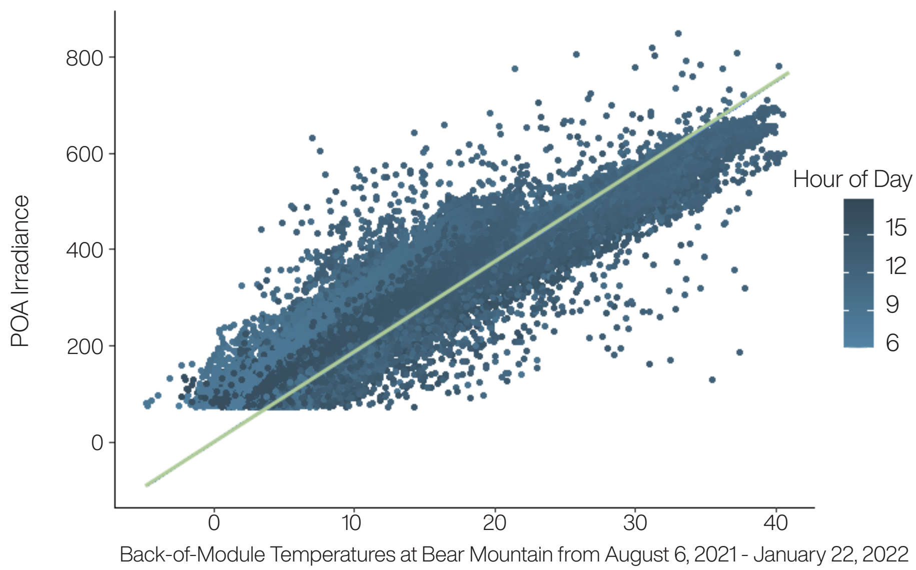

Figure 3 — Full five-month dataset of total heat dissipation at Bear Mountain, color-coded by hour of day

Furthermore, DNV observed that the appropriate U_C value "varies seasonally, with drier, warmer weather showing an effective coefficient near 15 W/m2K;" whereas in cooler weather, when the ground absorbs more heat, DNV noted that the U_C value reached above 25 W/m2K. This observation is represented in Figure 4, which shows the relationship between the U_C value and the time of year, as measured at the Bear Mountain site.

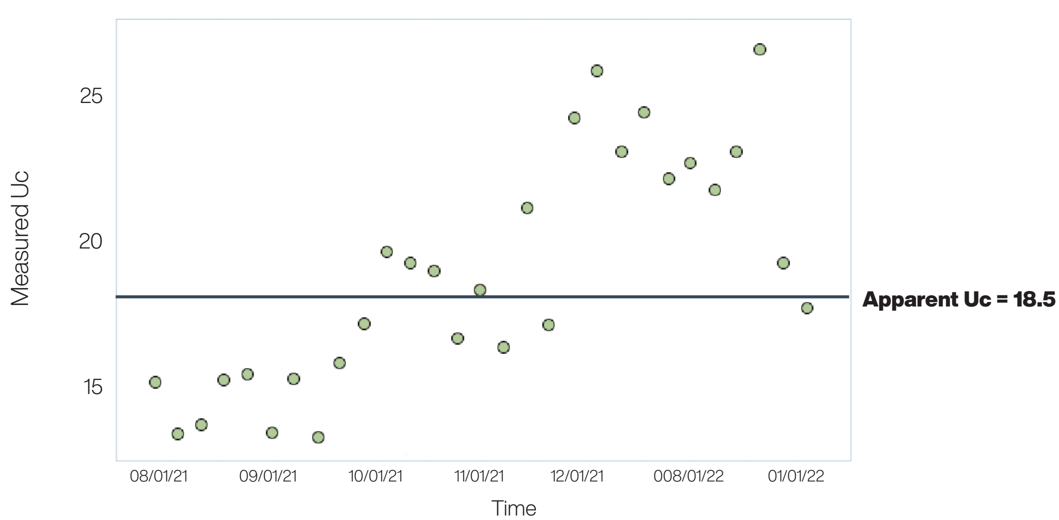

Figure 4 — Time-dependent U_C plotted over five months

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Based on the five-month dataset gathered at the Bear Mountain site, the DNV team estimated that an Apparent U_C "of 18.5 W/m2K and a convective heat transfer coefficient of 0 W/m2K/m/s are the most relevant values for use with Bear Mountain operational data."

The use of 18.5 W/m2K as an Apparent U_C value is further validated by the data presented in Figure 5. As you can see, the energy measured at the grid at the Earth Mount Solar® PV site is almost perfectly in line with PVsyst's modeled power predictions of the same system over the same five-month timeframe.

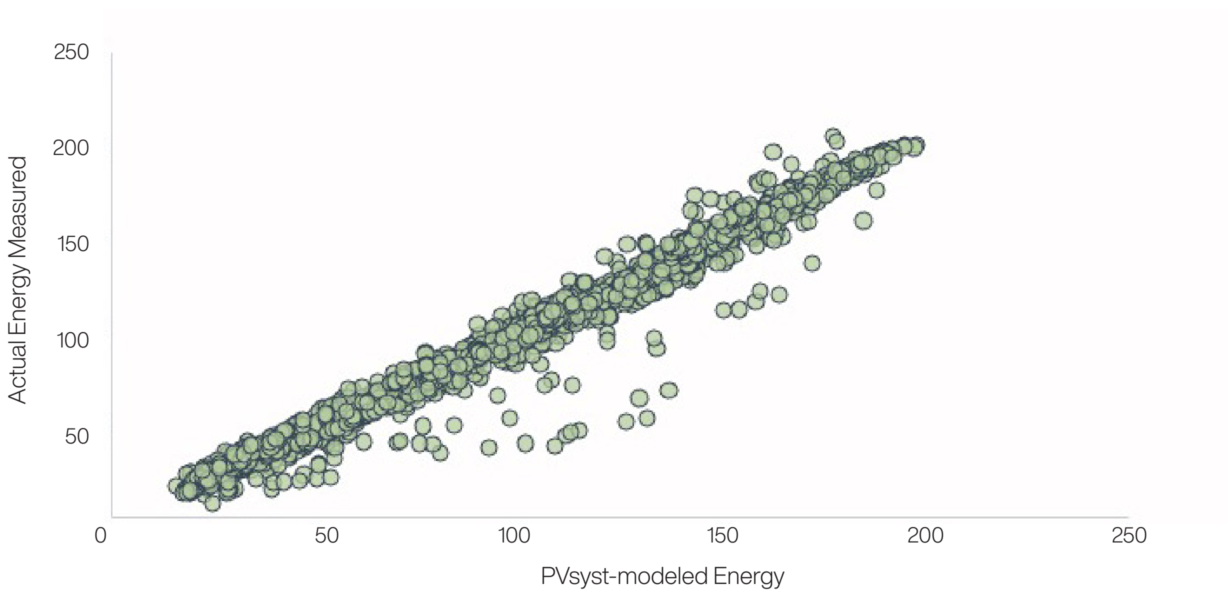

Figure 5 — PVsyst-modeled energy vs. actual energy measured

The Bear Mountain test data strongly suggests that 18.5 is a reliable U_C estimate for use in PVsyst, and therefore that the baseline energy performance of an Earth Mount Solar® PV installation can be accurately predicted with PVsyst using that value.

Results

With an estimated Apparent U_C value of 18.5W/m2K — based on five months of data collected in five-minute intervals, spanning all hours of each day over parts of three seasons — we can now compare the expected thermal performance and resulting energy yields of Earth Mount Solar systems to more traditional installation types.

We previously provided a table (Figure 1) that showed the heat dissipation and energy yield factors for the main traditional solar installation types in use today. Here, we have repeated that table with the Earth Mount Solar® PV values added.

As you can see, when factoring in the thermal dissipation properties of the ground (U_g), Earth Mount Solar® PV compares favorably to other widely used installation types.

PV Mounting Type	Heat Dissipation Values (U=W/m²K)	Energy Yield per 2MW Array
Flush Rootop PV (fully insulated backside)	U=15.5 Uc=15 Uv=0.5	4,580 MWh/year at DC:AC =1.44 Energy Yield Factor = 1
Ballasted C&I Rooftop PV w/ Tilt (partially insulated backside)	U=20.5 Uc=20 Uv=0.5	5,190 MWhr/year at DC:AC=1.44 Energy Yield Factor = 1.13
Earth Mount Solar PV (installed directly on the ground)	U=18.5-22.8 Uc=18.5 Uv=0.0	5,020-5,444 MWhr/year at DC:AC=1.71 Energy Yield Factor = 1.10-1.19
Fixed-Tilt and Tracker PV (open-air backside)	U=29 Uc=27 Uv=1.2	5,853 MWhr/year at DC:AC=1.33 Energy Yield Factor = 1.28

Figure 6 — Heat dissipation values and energy yield of common mounting configurations, including Earth Mount Solar

As noted already, and as evidenced in Figure 6, the Apparent U_c value of 18.5 is a conservative estimate provided by DNV that is intended to serve as a baseline of expected heat dissipation performance in an Earth Mount Solar® PV system. While this estimate already places Earth Mount Solar® PV installations well within the industry's widely accepted performance norms, the actual heat dissipation (U) value as measured at the Bear Mountain test site significantly exceeded this baseline prediction, with a total U value of 22.8 W/m2K. The difference observed in these values (18.5 and 22.8) is likely explained by the presence of the ground, which acts as a seasonally variable thermal sink that draws heat away from the underside of the Earth Mount Solar® PV array — a phenomenon not able to be modeled by the current version of PVsyst (v7.2), and the full thermal impact of which continues to be studied.

We will publish revised versions of this white paper as more data is acquired.

Summary

Earth Mount Solar® PV arrays experience significant heat dissipation — and high levels of overall energy performance — as a result of their installation directly on the ground in comparison to other installation methodologies that are characterized by limited air flow. This is because the ground acts as a thermal sink, pulling heat from the underside of the modules and cooling the system. This, in turn, leads to improved module efficiency and energy yield. Real-world data gathered at an Earth Mount Solar® PV project site over a span of five months confirmed and quantified the positive impact of ground-driven heat dissipation on the performance of the Earth Mount Solar® PV system.

Furthermore, DNV's analysis of this same data suggested that anyone using PVsyst to estimate the heat dissipation of an Earth Mount Solar® PV system use an Apparent U_C value of 18.5 W/m2K. This value will deliver reliable (if conversative) performance predictions that fall within the standard range of uncertainty. A PVsyst model using this value will establish a baseline of expected performance for Earth Mount Solar plants.

The results from Bear Mountain — both modeled and real — show that the Earth Mount Solar® PV system has achieved measured thermal performance that is comfortably within accepted industry parameters, with annual per-array energy outcomes that make it competitive with the highest-performing system configurations on the market today.

References

1. "Array Thermal Losses." PVsyst Website. https://www.pvsyst.com/help/thermal_loss.htm

2. Cameron, C.P., Stein, J.S., & Tasca, C.A. "PV Performance Modeling Workshop Summary Report." May 2011. https://www.osti.gov/servlets/purl/1018460

3. "Technology Assessment, Earth Mount Solar™ PV System." DNV Bankability Report. March 16, 2022.

4. Faiman, D. "Assessing the outdoor operating temperature of photovoltaic modules." Progress in Photovoltaics 16(4): 307-315. 2008. https://onlinelibrary.wiley.com/doi/10.1002/pip.813