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Inside PV CAMPER: A global research collaborative to advance photovoltaic performance across a range of operating climates

Research | As solar finds itself installed in further flung climes, so it must operate in harsher conditions. PV CAMPER, a collaborative effort including some of the world's leading academic and research institutes, has set itself the aim of uncovering data to help drive the industry forward. Here, members of PV CAMPER discuss some of their preliminary findings.

Propelled by the precipitous drop in costs, global photovoltaic capacity continues its steady upward trajectory, with an average annual growth rate of 15% and a doubling rate less than three years (IEA, 2020b, a). In fact—despite the broad economic impacts of Covid—2020 was a banner year for solar, with a record-breaking 160GW+ installed across the planet (IRENA, 2021), the result of lower costs, industry momentum and favorable policies.

One notable manifestation of this explosive growth is solar's spread to traditionally unfavorable climates, where for decades, costs were too high and energy yields too low for economic viability. But as costs continue to plummet, solar is rapidly gaining energy share in high-latitude countries like Norway and tropical nations such as Brazil, which has 7.5 GW of installed solar and an annual growth rate of 64%. Even Fairbanks, Alaska, at a latitude of 64° North, now boasts a 500kW utility-owned PV installation.

Ensuring high lifetime performance across increasingly diverse geographic regions, however, is a growing challenge, the result of multiple trends affecting the global solar economy. One unknown is how emerging higher-efficiency PV technologies (from redesigned cell interconnects and architectures to module-level innovations) will perform long-term in relatively new operating environments. Another concern is the uncertainty around climate change, which is upending traditional patterns of humidity and temperature, forcing scientists to rethink the definition of a typical meteorological year and assumptions about measurement uncertainty. The third area of uncertainty, also related to climate change, is the uptick in extreme weather: PV systems everywhere appear to be at greater risk from natural disasters, including hurricanes, dust storms, hail, blizzards, and wildfires.

Hourly meteorological data for Koeppen-Geiger climate zones are available for modeling purposes but the available data represents only six zones (temperate continental, temperate coastal, tropical humid, subtropical arid, subtropical coastal, high elevation), and is too low resolution to adequately capture local climate profiles, including dynamic shifts in such critical variables as irradiance, temperature and a module's response to spectral and angle-of-incidence changes.

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Attempts have been made to replicate climate-specific accelerated testing, but these lab-based attempts, which cannot replicate the precise stochastic and intermittent interactions of multiple field variables, are approximate at best.

Lacking good data on cross-climate PV performance, manufacturers have had little incentive to develop PV modules and systems customised for their operating environments, that is, designed for optimal performance and reliability in specific climates. Instead, PV is largely viewed as a one-size-fits-all commodity and the majority of deployed modules are manufactured and sold without consideration for designing or matching those technologies to the geographic region in which they will be installed.

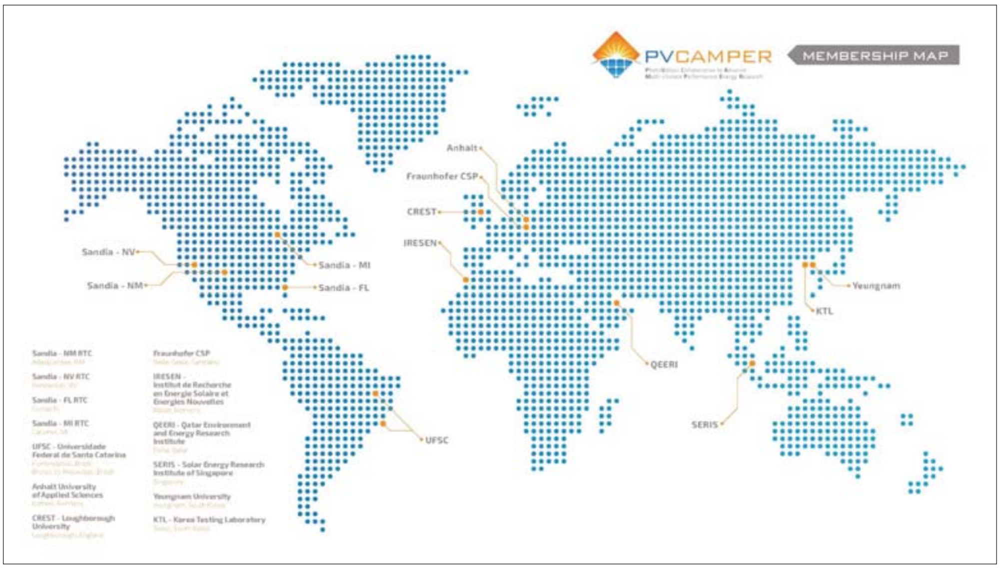
Energy ratings in compliance with IEC 61853 are a step toward climate optimisation but fall drastically short of what is needed.

This article makes the case that high-fidelity ground-based measurements of performance variables, across multiple climates and operating environments, are critical to both accurate predictions of energy yields and also to informing the development of module technologies that are operationally more efficient. To have confidence in those measurements, however, requires building a technical foundation for quantifying the factors that influence the long-term performance and degradation of photovoltaic systems, thus increasing the amount of data generated while reducing measurement uncertainty.

To achieve that goal, researchers must have access to high-fidelity data across different climate zones and also engage collaboratively on data collection and analysis. Given the importance of this data in enabling a global solar economy, the purpose of this article is to describe a newly formed collaborative, which has prioritised cross-climate research, along with an overview of the organisation's current research priorities, with an eye to encouraging broader participation, by both industry and research organisations.

The Photovoltaic Collaborative to Advance Multi-climate Performance and Energy Research (PV CAMPER)

Better known by its acronym, PV CAMPER, the Photovoltaic Collaborative to Advance Multi-climate Performance and Energy Research represents a global network of research institutions collectively committed to tackling key challenges in the global solar sector, i.e., the need for more accurate performance



Credit: PV CAMPER

Figure 1. World map depicting the locations of PV CAMPER member institutions and their associated field sites (Sandia National Laboratories, 2021a).

models and levelised cost of energy (LCOE) calculations, and for breakthrough advances in the performance, reliability and value of PV systems across the world's climate zones. If PV CAMPER succeeds, its success will lie in providing the data needed to help the industry improve its technologies, instrumentation and performance calculations.

Although multiple international organisations promote networking and research, among them the International Energy Agency, the International Photo-Voltaic Quality Assurance Task Forces, and the PV Performance Modeling Collaborative, PV CAMPER brings a unique angle to global research by being both an intellectual (expert-based) and a physical (multi-site) entity.

At its core, PV CAMPER is a network of plug-and-play field sites, a community of researchers with a track record of working together, and a portfolio of research projects aimed at improving the efficiency and reliability of PV components and systems. The organisation differentiates itself from other collaborative groups by its (1) common research platform, with instrumentation of comparable quality and common O&M protocols.; (2) strategic focus on international research, that is, on performance and measurement challenges, ranging from soiling-loss factors to humidity and temperature oscillations to instrument drift and measurement uncertainty; (3) cross-climate field-validation services for emerging technologies; and (4) early-warning capabilities for climate-induced risks and failure mechanisms.

What began as an informal gathering of researchers in 2018 is now a formally recognised organisation, with 11 member institutions and a 16-site network of field labs distributed across both hemispheres and most major climate zones. Led in its early years by Sandia National Laboratories, which manages a similar, but smaller, network of field labs called the US Regional Test Centers for Emerging Solar Technologies (SANDIA NATIONAL LABORATORIES, 2021b), PV CAMPER is now governed by an executive committee and chaired by Fraunhofer Center for Silicon Photovoltaics.

Other members of the executive committee include representatives from Sandia, Anhalt University of Applied Sciences in Germany and the Universidade Federal de Santa Catarina in Brazil. Per the terms of PV CAMPER's organisational charter, members must meet a set of clearly defined technical requirements for instrumentation quality, calibration practices and characterisation procedures; they must also commit to participating in at least one collaborative research project a year and to leading one or more projects every few years. In addition, the charter specifies attendance and research participation, and defines a governance structure that promotes organisational stability and continuity, with an executive committee whose members rotate on an annual basis to ensure full member representation

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This strong global network of sites, with common designs, instrumentation, protocols and standards, has enabled PV CAMPER to focus on a set of inaugural research initiatives that support the collection and analysis of :

- Albedo and other irradiance data, to inform performance models, and increase their accuracy and applicability
- Geographically diverse data to help address ongoing and widespread performance challenges, such as soiling-loss factors, cloud persistence, humidity and temperature oscillations
- Performance data to validate the cross-climate performance of emerging technologies and also climate-specific PV designs

Bringing greater accuracy to the quantification of PV performance

Measuring and quantifying the multiple factors that contribute to a PV system's performance is essential to lifetime yield projections and precise return on investment calculations. However, high-confidence data is hard to come by: the specific variables that contribute to the long-term performance and degradation of PV systems vary greatly according to location, notably spectral qualities, temperature range and oscillations, humidity levels, soiling rates, etc.

In addition, the data that is meant to accurately represent those variables may itself not be accurate, depending on the source (measured versus satellite) and the quality, calibration, and maintenance of the instrumentation, including its accuracy range, and the frequency with which data is collected (STEIN; KING, 2013). As a result, and in the absence of a set of best practices or standards for measuring and predicting the field performance of PV systems, a significant amount of measurement uncertainty exists, resulting in an even higher potential for measurement error.

PV CAMPER therefore considers the quantification and reduction of measurement uncertainty, which in turn directly affects the accuracy and global applicability of performance models,

Figure 2. Pyranometers, such as the plane-of-array sensor shown here, require periodic calibration to maintain their accuracy. What is unknown, however, is how local climatic factors affect calibration drift and therefore how much measurement uncertainty exists across different operating environments.

to be a key research objective. To that end, PV CAMPER has made generating and validating a set of best practices for cross-site data collection an important priority. Comparing data from different sites is only possible when common instrumentation, common O&M protocols and common validation techniques are respected and employed, a defining feature of the collaborative.

To illustrate the scope and impact of PV CAMPER's research activities, three ongoing projects are described below, one focused on the measurement accuracy of pyranometers, another on the measurement and modeling of albedo, which is a key contributor to bifacial gain, and a third on condensation as a factor in soiling losses. All three projects, both individually and collectively, offer benefits to multiple stakeholders, among them researchers, manufacturers, developers, investors, underwriters and asset owners.

Assessment of pyranometer drift and measurement uncertainty

Because irradiance is the single most important determinant of a PV system's performance; this work aims to identify climate- and installation-specific variations in solar irradiance measurement uncertainty, and to quantify the dominant uncertainty contributions in each case so that PV plant operators may improve their system performance assessments and system health diagnostics in the most cost-effective manner.

Irradiance measurement data underpins PV system performance assessment, meaning that uncertainty in this parameter directly affects the accuracy of the Performance Ratio calculation, as well as any other indicator normalised to the input solar energy.

While existing standards for PV system monitoring (e.g. IEC 61724) specify a maximum permitted calibration uncertainty, the overall in-field measurement uncertainty is not explicitly considered. The calibration uncertainty is an important contribution to the overall total, but there are many others: influences such as linearity, temperature and solar angle of incidence to the sensor are known, but rarely quantified in practice.

Historically, the lack of measurement fidelity was justified by the limited deployment of monitoring sensors and by the significant uncertainty in electrical output data captured by sensors used for energy monitoring. However, as the quantity and quality of string-level and even module-level data has increased in recent years, system diagnostics have also evolved from a simple plotting of energy output against time, to the monitoring of PV behavior under specific or normalised conditions.

As a result, there is now a greater need for more accurate determination of those conditions (especially irradiance). Furthermore, the rapid pace of technological evolution, including the deployment of bifacial and/or partial tracking systems require ground-reflected irradiance measurements, irradiance fluxes that differ significantly from typical sensor calibration conditions (high irradiance, low or zero angle to the sensor) and are non-uniform across the back of an array. This study is therefore focused on the full characterisation of multiple sensors, coincident with case studies of deployed use, to determine the boundary conditions for calibration and their impact on final uncertainty.

The main challenges are the development of significant full-characterisation methods, at a cost that is reasonable and practical to use, and the sourcing of a wide range of different system installation types and operating environments. Fortunately, the PV-CAMPER collaborative is made up of partners distributed across the globe in many different operating climates, with access to commercial PV systems of different designs and operating the highest quality research laboratories.

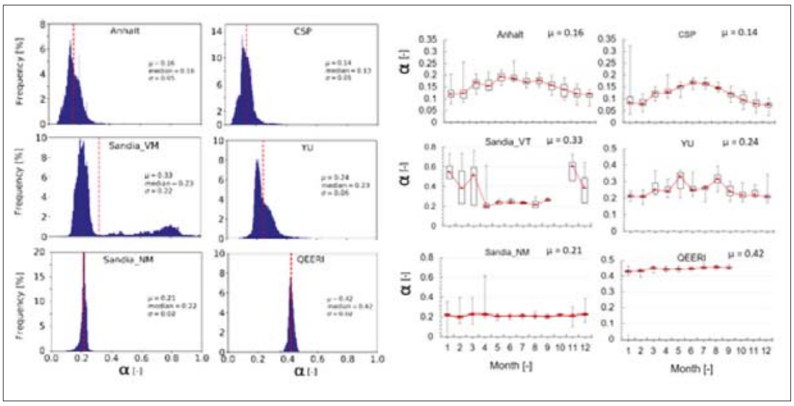
So far, the study has focused on quantifying variation in the angular response of different pyranometers, using different calibration methods, which provides plant operators the choice of either a more reliable uncertainty envelope, or to calculate a point-by-point uncertainty. The next phase will determine the influence of operating climate on rates of calibration drift, to provide data-based decision-making on the necessary frequency of sensor recalibration. The ultimate goal is to develop readily implemented full-characterisation methods, at a cost that is reasonable and practical to use across a wide range of system installation types and operating environments.

A study of the accuracy of ground-based albedo measurements versus satellite-based data

Albedo, the diffuse reflectivity of a surface, is an important measurement in PV performance evaluation and simulation, especially for bifacial module technologies, which are rapidly gaining market share. Yet many performance models assume albedo is constant over time for a particular substrate, even when evidence shows that albedo values can shift dramatically based on sun angle, seasonal irradiance, type and seasonal variation in vegetative ground-cover, degree of backside shading, presence and degradation of snow, and prevalence of airborne particulates, such as soot, that absorb light. Only by quantifying the temporal and spatial variation in albedo

Table 1: Site description

Site	Country	Lat., Long.	Climate zone
Anhalt	GER	51.77°N, 11.76°E	Cfb
CSP	GER	51.49°N, 11.93°E	Cfb
YU	South Korea	25.32°N, 51.43°E	Cwa
Sandia_VT	VermontUSA	44.47°N, 73.10°W	Dfa
Sandia_NM	New MexicoUSA	35.05°N, 106.54°W	Bsk
QERRI	Qatar	35.83°N, 128.75°E	Bwh



Credit: PV CAMPER

Figure 4. Preliminary results of one-year albedo data with different measurements setups: (left) - Histogram of α for each test site together with mean (μ), median and the standard deviation (σ), (right) - Seasonal variation, monthly average of rear/front side ratio, (Sandia_VT: no data for October, QERRI: 9-month data only) (DITTMANN et al., 2019).

measurements can one accurately predict the performance of bifacial systems.

Equally concerning is the lack of standards for ground-based albedo monitoring. Typically, ground-based measurements rely on dual-pyranometer instruments, which consist of a class A pyranometer horizontal to the sky, and a "low cost" class C pyranometer horizontal to the ground, although sometimes combinations of pyranometer/reference cells or even reference cell/reference cell are employed. Most such instruments are fixed in place and their height can vary.

Lacking a set of best practices or standards for measuring albedo creates data inconsistencies and introduces significant measurement uncertainty, with diurnal and seasonal changes in albedo and uneven backside shading rarely considered. As a result, the potential for measurement error can be significantly higher than recognised.

With the participation of five CAMPER member institutions and the deployment of high-fidelity albedometers (dual-pyranometer instruments) across six geographically diverse sites, the objectives of this study are to:

1) Establish a set of best practices for ground-based albedo measurements, including type and placement of instrumentation, and calibration and maintenance protocols;
2) Measure diurnal and seasonal shifts in albedo across difference climate zones and for multiple years;
3) Quantify the reduction uncertainty in albedo measurements by the above technical approach;
4) Validate simulation methods for rear-side irradiance.

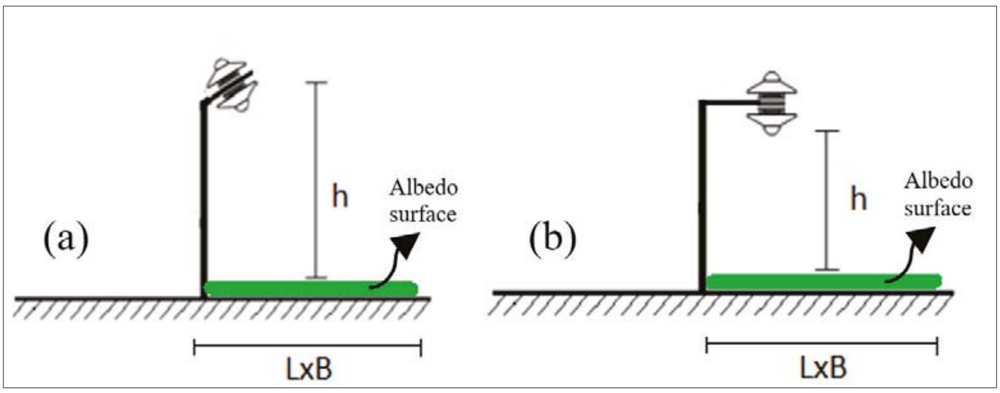
Preliminary data collected from six sites are displayed in Figure 4. Two of the sites (Sandia, New Mexico and QEERI in Doha, Qatar) show relatively little deviation in albedo throughout the year, a fact attributable to a relatively consistent climate. In contrast, the one site that sees persistent snow in winter (Sandia, Vermont) shows clear spikes in albedo five months of the year.

Table 1 provides the location, geographical coordinates, Köppen-Geiger climate classification [7] and the measurement period for the six sites included in this study. Three sites are located in temperate climates (Anhalt/CSP in Germany and YU in South Korea) while Sandia_VT (Vermont, USA) represents a humid continental climate. Sandia_NM (New Mexico, USA) and QEERI (Qatar) are located in cold desert climate and a cold semi-arid climate, respectively.

Figure 4 (left) shows the histogram of α for each test site together with mean (μ), median and the standard deviation (σ). In moderate climates, α is more widely distributed around the mean, while in the desert climates the distribution is very narrow. At Sandia_VT two maxima are formed in the distribution. One around 0.2 which represents the summer months and around 0.7 which represents the winter months with persistent snow cover.

Figure 4 (right) shows the monthly mean value of α in a box plot diagram. Seasonal variation at Anhalt can be attributed to changes in vegetation as the grass turns from green to yellow/grey to brown. At CSP, the albedo similarly reflects vegetative changes but is also affected by the shading of nearby PV modules. In contrast, the constant albedo measurements at QEERI are indicative of a consistent climate and highly reflective substrate. The data from Yeungnam University in Korea should similarly show low variability, but in this case the sudden upticks in May and August can be attributed to artificial whitening of the substrate.

Overall, this work demonstrates that albedo or the rear/front side irradiance ratio (α) can vary over time, depending primarily on the substrate type as well as the local climate. If not carefully considered, all these effects can have



Credit: Anhalt University of Applied Sciences in Germany.

Figure 3. Representative albedometers, with upward and downward-facing pyranometers, one set at a tilt angle representative of plane-of-array irradiance; the other one horizontal to the ground (h=1.5m).

a profound impact on the uncertainty of performance projections. This work speaks to the importance of applying standardised and reliable measurement methods to multiple sites to reduce measurement uncertainties and to increase the accuracy of performance models and associated LCOE calculations for bifacial PV plants.

The effect of condensation on PV soiling rate – A global study

It is well known that condensation (dew) plays a major role in PV soiling. The main effect is that moisture traps dust particles to the module surface, and it can also "cement" the dust in place after the condensation dries out. On the other hand, if there is a lot of condensation it can run off the modules and in fact clean them.

Despite these important effects, the quantitative link between condensation and PV soiling rate is not well known. The main reason is that condensation sensors (and data) are not common — such sensors are not included in usual weather stations, and there are few "industrial grade" products available in the market for standalone use.

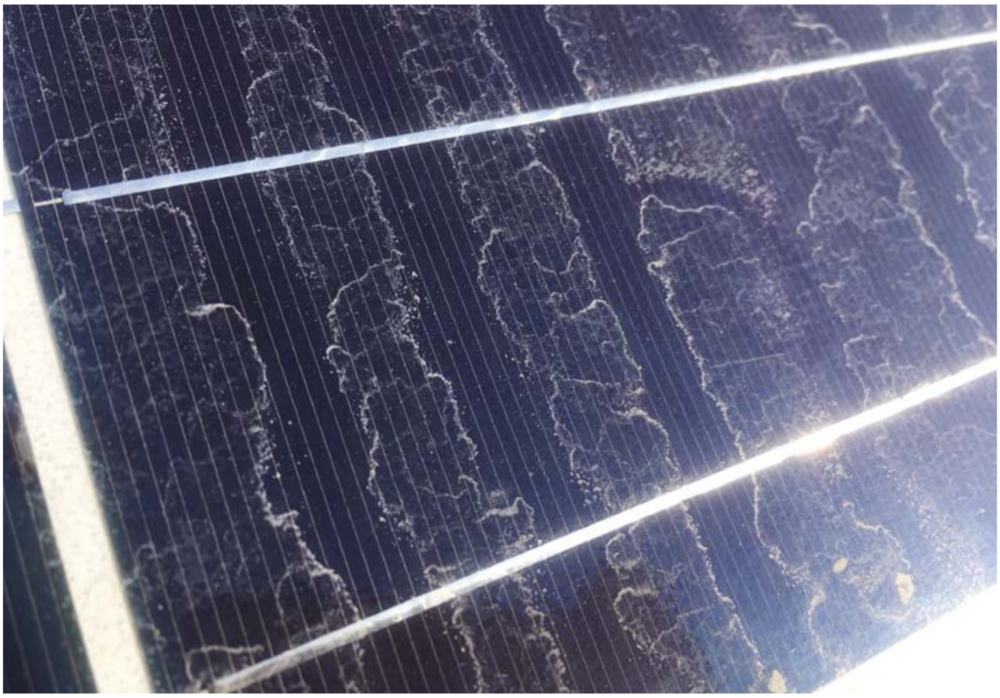
The goals of this PV CAMPER study are twofold: First, to develop and validate an inexpensive condensation sensor for use with PV systems; and second, to deploy such sensors globally to study the effect of condensation on the PV soiling rate, in different environments.

The study is led by QEERI, and currently involves nine PV test sites run by PVCAMPER and other organisations. The condensation sensors were developed and validated by QEERI in 2019-20, and confirmed to give similar values as a commercial reference sensor (costing roughly 100 times as much). QEERI began making and supplying condensation sensors for the project participants from mid-2020.

As well as condensation, participants measure other meteorological conditions and the PV soiling rate at their sites. The data is being consolidated and verified by QEERI. So far, the goal of achieving a wide variety of condensation and soiling conditions has been met. It is expected that by late 2021 sufficient data will be available for robust statistical analysis of the effect of condensation on PV soiling rate in different climates. Hopefully, this information will help improve predictive models of PV soiling rates, and improve physical understanding of the soiling process.

Conclusions

As the global solar economy continues to expand and diversify, a coordinated research effort is needed to 1) ensure the performance and reliability of emerging technologies across different operating environments; 2) support the development of technologies that are climate optimised; and 3) build greater confidence in lifetime energy predictions for PV systems by improving the accuracy of performance models and the data that feeds into them. PV CAMPER has stepped into that void, providing both researchers and industry partners with a technical platform for reducing uncertainty in the solar sector and a scientific basis for technological evolution that recognises solar is not a one-size-fits-all commodity.



Credit: PV CAMPER

Figure 5. Condensation is important and complex in PV soiling because it can trap dust particles but also remove them

Acknowledgments

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