A case for accuracy: Pyranometer or satellite irradiance data?

Irradiance data | Accurate irradiance data is key for assessing the feasibility, profitability, and performance of solar energy assets. 3E and Kipp & Zonen investigate the benefits of combining pyranometer and satellite-based irradiance data for optimal planning and operation of PV plants

Policy makers, project developers, investors, asset managers, owners and O&M contractors base their daily operations and decision-making on accurate solar resource information. Developers, lenders, and investors need assurances when evaluating the feasibility, the financial profitability and the risk of a project. If the system does not produce the predicted energy, large financial penalties that require expensive risk mitigation measures may apply. Precise solar irradiance data is essential to produce robust PV energy yield predictions. Moreover, the quantification of uncertainty in the solar resource and the resulting PV energy yield is especially important for evaluating the financial risk of PV investments. An error of just a few per cent in irradiance measurements, together with small and unnoticed plant under-performance, can easily result in lost annual revenues ranging from tens of thousands of Euros for a 5MW installation up to a million Euros for a 250MW plant.

During the operational phase, owners, asset managers and O&M contractors need unambiguous KPIs for an efficient and profitable operation of their portfolios. Adequate monitoring of a PV plant is crucial to evaluate its performance and improve the operation and maintenance of it. Irradiance data is the most important environmental factor determining the production of the solar array. Accurate irradiance measurement is essential for determining the overall performance of a solar park, since the energy provided by sunlight on earth (irradiation) has a relevant variability, both in space and time. As shown in Figure 1 on the following page, (irradiation data from 32 meteorological stations spread throughout the Netherlands), there is a considerable spatial and temporal variation, even over a relatively small and geographically uniform area such as the Netherlands. Figure 1 particularly highlights the yearly variability compared to the yellow line that shows the 10-year moving average.

A combination of satellite and pyranometer irradiance data is preferable when planning and operating PV power plants

Improving bankability of PV projects during the design phase

Reliable and independent historical solar irradiance data is required for the assessment of the long-term forecasted solar resource and PV plant yield. Increased solar data accuracy informs the financing of solar projects and accelerates investments. High accuracy historical irradiance data covering a period of more than 10 years and clear information on uncertainty is required to produce bankable reports.

The effect of the accuracy of the solar data source and its impact on the bankability of a project is shown in Figure 2 on the following page. For illustrative purposes, a comparison of two data sources with different accuracies is presented. A simplification is made using a normal distribution assumption to allow an easier comparison of the effect of different accuracies and their impact on indicators like, for example, P90 (90% probability of exceedance). In the example, an uncertainty of ±3% is considered for a state-of-the-art satellite-

Irradiance data

In this article, we focus on the two most common sources of data for Global Horizontal Irradiance (GHI):

1. On-site ground measured data
2. Data derived from satellite instruments measurements

The local irradiance is usually measured by a pyranometer and is very accurate (low uncertainty, if the equipment is well installed and maintained). When averaged and/or integrated over relatively short periods from as little as a minute to an hour, a pyranometer is the most accurate solution. But data derived from satellite imaging comes close to the on-site measurement uncertainty over longer time periods such as several days, months and years. Best practice is to use both on-site pyranometers and satellite data services to obtain accurate irradiance data for solar plant performance monitoring over both short and long time-scales.

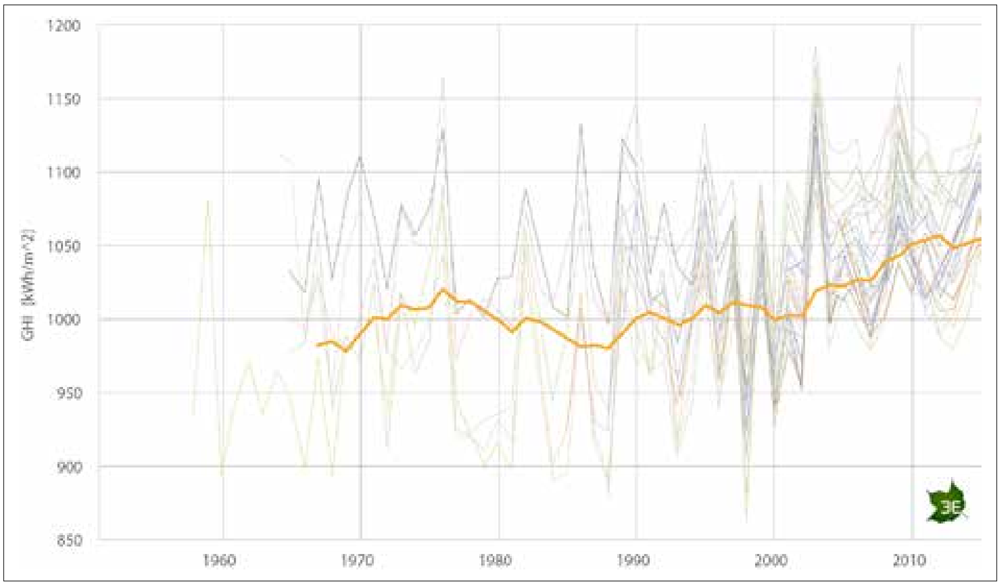

Figure 1. Annual GHI from 32 meteorological stations from KNMI in the Netherlands (orange line = mean 10-year moving average irradiation). An example of well-collected data with irradiation differences between years and up to 4% off the average (orange line)

based irradiance data provider (which can be even lower as shown in [1–3]) and an uncertainty of ±5% is considered for the other data source to highlight the effect of only ±2% difference in accuracy.

The effect of the propagation of this uncertainty into the final expected yield (kWh/kWp) for both a P50 and a P90 scenario is shown in the example (Figure 2), where using a data source with lower accuracy (red line) results in a much lower P90 value impacting the bankability of the project. A higher P90 value resulting from the use of a higher quality solar data source like 3E's satellite-based solar irradiance data results in higher debt leverage for the investor since the Debt Service Coverage Ratio (DSCR) is not limited by a lower yield (EBITDA) from the project. The higher the yield, the less equity the developer must invest, resulting in more attractive financial indicators.

For example, for a typical 5MW European solar power plant, and considering a DSCR of 1.2, a 2% difference in P90 when using a higher quality solar irradiance data source such as 3E's satellite-based solar data [3, 4] results in higher lending capacity and thus ca. 9% less equity for the investor. Or, to put it another way, the investor can increase his return on equity (ROE) by 10% compared to a situation where medium quality data has been used.

Detecting underperformances during operation

Undetected under-performance can easily cause the performance ratio of PV assets to drop below a contracted value, resulting in financial penalties. Investment in good quality irradiance measurement equipment usually pays back within one to two years. During the O&M of a PV asset, having a second independent solar irradiance data source is crucial for revenue and yield reporting, considering that many local sensors may be faulty or that there is often missing data. The solar irradiance data is key for the calculation of production losses, optimisation of maintenance interventions and contractual reimbursement in case of underperformance.

The importance of accurate irradiance data is shown in Figure 3, opposite, for a degrading 5MWp PV plant: the contractual performance ratio is plotted in orange (taking a small, predicted degradation into account). There is a badly maintained, low-quality, degrading on-site sensor (dashed lines for monthly and six months PR) and high-quality irradiance data (solid lines for both monthly and six months PR) available. The figure indicates that in this case the contractual performance ratio threshold would get triggered nine months later due to bad irradiance sensing.

The value of irradiance data to solar plant stakeholders

As an example, let us consider a typical 5MW European solar power plant: it produces 1,200kWh/kWp, the electricity is sold at €120/MWh, expected annual revenues are €700,000 and contracted annual O&M costs are €50,000 [1]. In Table 1 (facing) the value of accurate irradiance data is quantified for each of the different stakeholders involved in the asset operations.

On-site measured irradiance data

On-site irradiance data is collected by sensors placed at well-chosen locations in a solar park and they must be able to reliably measure irradiance differences of a few per cent over long time periods, as shown in the annual irradiation chart

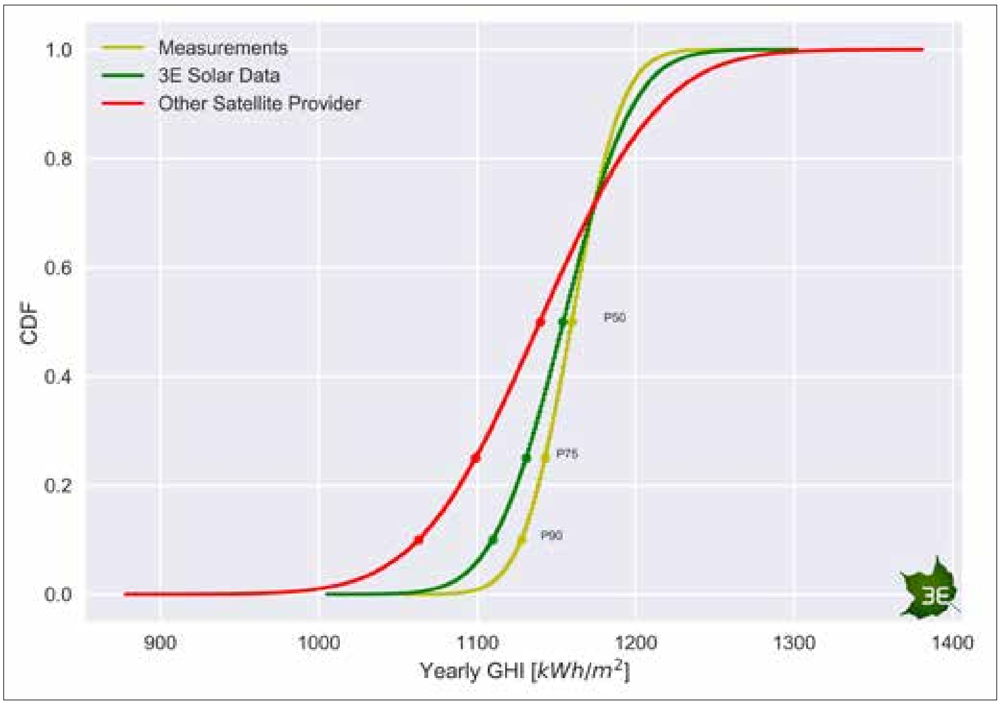

Figure 2: The importance of accurate long-term irradiance data when calculating indicators such as P50/P90 for the bankability of a PV project

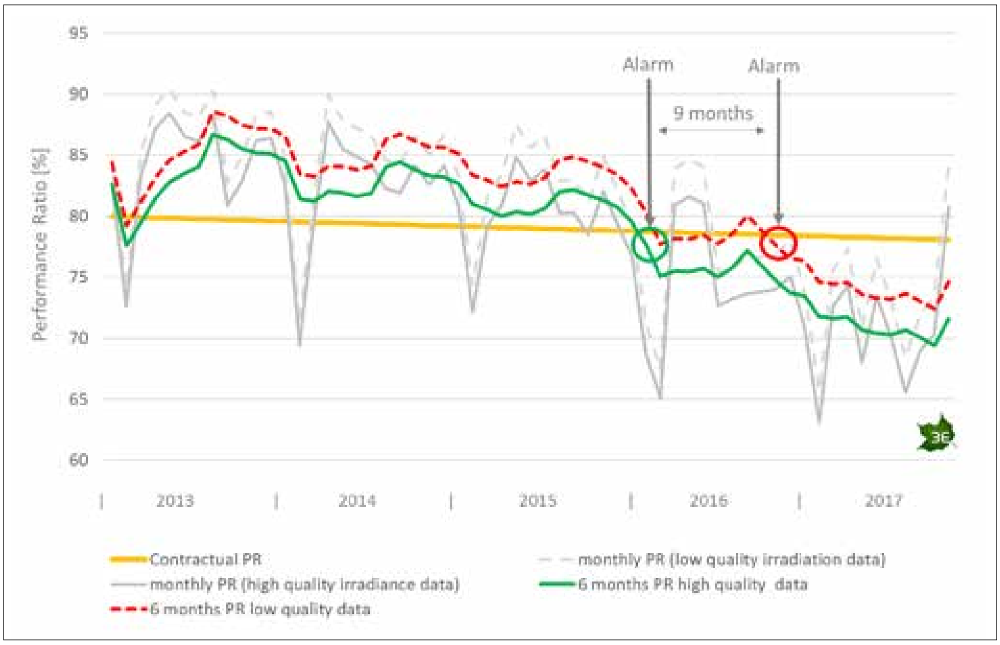

Figure 3. The importance of accurate irradiance data when detecting operational underperformances

for the Netherlands. By specification, ISO 9060:2018 Class A and ISO 9060:1990 secondary standard pyranometers (e.g. Kipp & Zonen CMP10 or SMP10 [5]) are most suited for the job. Their modest price, compared to the multi-million euro investments in a solar project, and their role in plant performance monitoring and fault and degradation analysis, imply that the business case for installing these instruments is very positive.

Figure 4: Kipp & Zonen CMP10 or SMP10 pyranometer

On-site data is needed for real-time and short-term performance monitoring for analysis of solar plant issues (e.g. panel or system degradation) and for maintenance and repair decisions. It is also used to fine-tune the satellite data for the local conditions.

Two separate local solar irradiance measurements are necessary:

1. Irradiance in the horizontal plane - Global Horizontal Irradiance (GHI)
2. Irradiance at the same tilt and orientation as the solar panels, often called Plane of Array (POA) or Global Tilted Irradiance (GTI)

On-site POA measurements are most important, since this parameter is a major input for monitoring the expected yield and performance of the solar plant. Unlike GHI, POA takes into account radiation reflected from plant structures and the ground that are in the view of the PV panels and of the tilted pyranometer. For example, the reflection of white sand is much higher than that of black soil (Figure 5, following page).

To collect high-quality on-site irradiance data, the pyranometers must be installed precisely and maintained well, with regular dome cleaning, alignment checks and recalibration. On larger plants,

EPC	O&M contractor	Asset manager/owner	Debt finance/investor
When developing, designing and building a utility-scale solar energy power plant, the most cost-effective irradiance measurement solution that is compliant with the specifications brought forward will normally be chosen. However, during the various stages of acceptance testing, irradiation measurements become critical to justifying the plant performance.	As an O&M contractor on a large portfolio of solar assets, it is important to have adequate, cost-effective, reliable and indisputable irradiation monitoring.	Managing solar assets is about contracts and performance, including guarantees and indemnities for underperformance. Without reliable data, particularly for irradiance, Performance Ratio calculations are meaningless, degradation becomes undetectable and availability cannot be calculated.	Short-term performance issues of the assets are not very relevant. However, in order to assess Debt Coverage Ratio (DCR) versus the business plan, medium-term to long-term plant performance issues should be distinguished from irradiation differences.
A clear irradiation monitoring approach, with a well designed and implemented measurement chain, is therefore key to avoiding lengthy performance and availability discussions that delay payments. Expensive on-site corrective interventions due to mounting, cabling, calibration, communication or placement issues can be avoided.	High-quality on-site measurements of performance parameters with remote analysis (including irradiance) lead to efficient problem solving (with or without a site visit) and contribute to the margin on the contracted O&M fee.	Data integrity, maintenance and the re-calibration of on-site pyranometers (and other measurement equipment) should be part of the contract with the O&M contractor.	A reliable source of site-specific irradiation data is key to being forewarned of up-coming debt finance issues.
Example case: *Typical outstanding payment at the Provisional Acceptance Certificate (PAC) stage on a 5MWp project is in the order of €200,000. Delayed payment hinders the cash position and therefore investments in new project developments. At the Intermediate Acceptance Certificate (IAC) and Final Acceptance Certificate (FAC) stages, poor irradiation policies can result in significant liquidated damages for the EPC. Typically, for a 5MWp plant, if 2% under-performance is suspected, the penalties at stake could also be in the order of €200,000.*	***Example case:*** *Typical O&M fee on a 5MWp project is in the order of €50,000 per year, while annual revenues amount to €700,000. The cost of going on-site differs per location (determined by travel costs and wages) but one day on-site for in-depth local investigation and fault analysis typically costs €500-1,000.*	***Example case:*** *An undetected performance degradation of 2% over five years can result in a revenue loss of €70,000.*	***Example case:*** *Working with high probability (P90) scenarios for solar assets requires high quality, validated irradiance data as an input and the asset manager should be able to report degradation figures. As previously mentioned, an undetected performance drop of 2% over five years could result in a loss of €70,000.*

Table 1. The value of accurate irradiance data for each of the different stakeholders involved in the asset operations

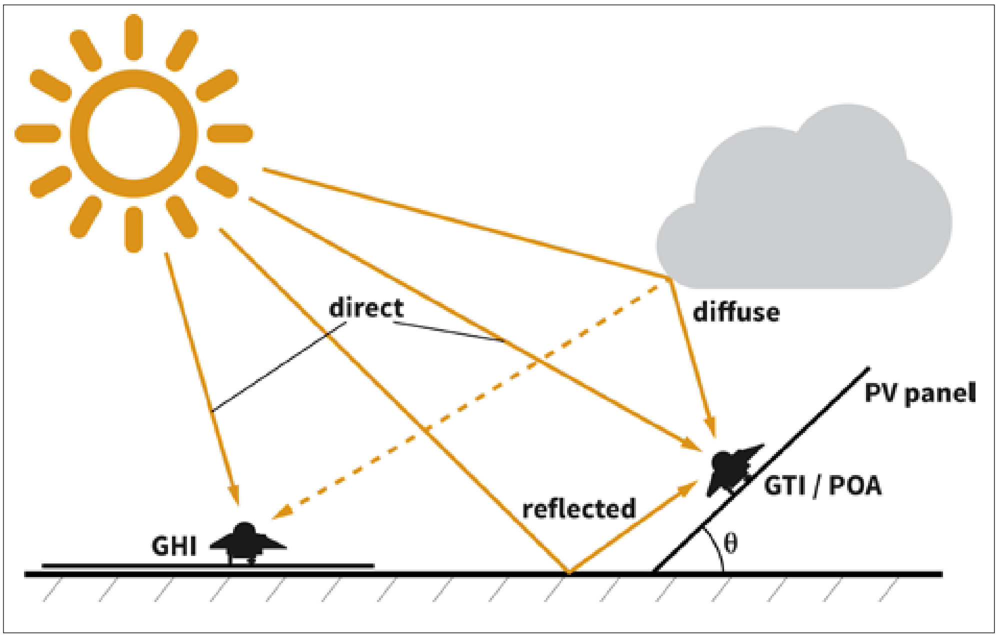

Figure 5: Global horizontal irradiance (GHI) and plane of array irradiance (POA) measurements

measurement at multiple points is necessary to increase measurement accuracy as clouds transit the site and where panel arrays are installed at different angles (for example on a hillside).

Additional pyranometers are advisable for redundancy and for backup during recalibration. If one pyranometer mounting becomes distorted, for example by a mowing lorry or a cleaning robot, a second pyranometer nearby will indicate that something is wrong. This happens more often than you might think! Intercomparison with additional pyranometers and/or satellite data will tell you where the problem is.

How many pyranometers?

The number of pyranometers, and their placement on a solar plant, is a subject of discussion in the utility-scale solar power market. Internationally accepted guidelines, such as the Project Developer's Guide, Utility-Scale Solar Photovoltaic Power Plants (IFC 2015) and the recent standard IEC 61724-1:2017 Photovoltaic System Performance Monitoring, provide recommended minimum numbers of pyranometers for different plant capacities.

However, these minimum numbers do not take into account:

- Differing environmental conditions across a large solar park, such as near or far shading effects, surface reflections, micro-climates, cloud transit times and dust accumulation (soiling);
- Plant design division into subsystems: strings, MPPs, inverters and differences in panel orientation & tilt;
- Redundancy: continuous measurement during service and calibration of pyranometers and backup in case of faults.

In general, substantial (environmental or design) deviations within a solar park need to be covered by separate, representatively positioned, pyranometers.

Maintenance

Pyranometers require some maintenance to ensure accurate measurements and this should be incorporated into every O&M planning schedule. In particular, the dome needs regular cleaning and the alignment (horizontal or plane of array) must be checked after cleaning. Recalibration is generally recommended every two years.

PV plant size	Minimum number of Class A/Secondary Standard pyranometers	
	Horizontal	Plane of array
<5MW	1	2
5-40MW	2	4
40-100MW	3	6
100-200MW	4	8

Table 2. Recommended minimum number or pyranometers for a solar park of uniform layout and topography

Irradiance measurement chain

Just fitting a high quality pyranometer is not enough, the entire data collection and analysis process must be robust and secure:

- Use Class A or Secondary Standard pyranometers for low measurement uncertainty.
- Sampling and logging intervals of the irradiation data:
  - o Sample every 1-3 seconds
  - o Log the average of the samples every minute
- Use a good quality scientific data logger for unamplified pyranometers (CMP10).
- Record the Modbus® digital data of Smart pyranometers (SMP10).
- Use statistically sound data analysis in the plant monitoring software, such as in SynaptiQ [6].

High-quality, site-specific solar irradiance data is the key to meaningful plant monitoring.

Satellite-based irradiance data

Satellite irradiance data is increasingly being used in both, utility-scale solar parks and in smaller installations since it is easy to acquire. A simple subscription to a service provides high availability of data with good time resolution and spatial coverage. Furthermore, for most locations on earth, in addition to near real-time data, satellite data is available going back at least 10 years providing a useful historical database for site prospecting and for optimising the site-specific design of solar power plants. Therefore, this source of irradiance data is often used as an input for long-term yield assessment and to calculate a reference yield for monitoring and business reporting.

Satellite irradiance data is retrieved using models to derive cloud, precipitation, and other parameters from measurements by optical instruments on board satellites. State-of-the-art satellite irradiance data providers such as, for example, 3E's Solar Resource Data Service [4] use advanced cloud physical properties (CPP) models. The use of CPP models has increased significantly the accuracy of satellite-based irradiance data throughout the day and under complex cloudy conditions.

How accurate is satellite-based irradiance data?

Satellite-based irradiance data can be extremely useful when available at high temporal and geographical resolution.

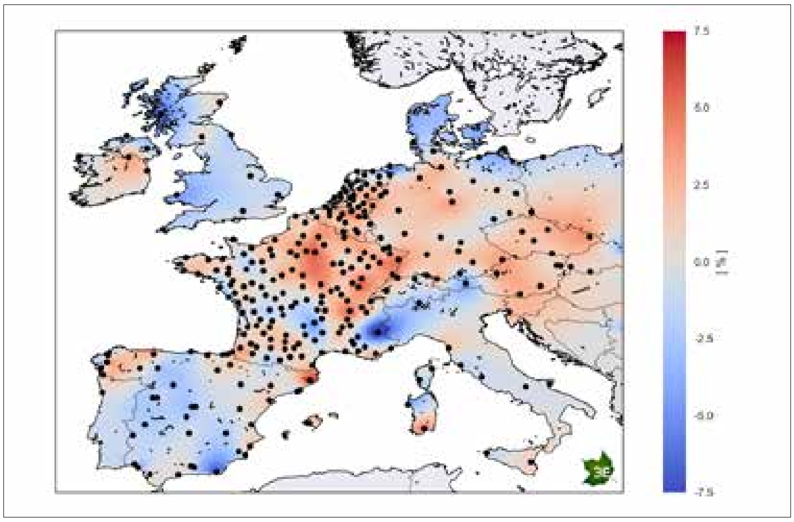

Figure 6: Percentage difference between 3E Solar Data and ground station data measured over one year with high-quality pyranometers maintained by the national public weather services in Europe

State-of-the-art satellite irradiance data providers are constantly evaluating their models against the reference data from the measurement stations ensuring their high quality. A recently published independent validation study performed by TÜV Rheinland shows that the percentage difference (bias) between 3E's satellite-based solar irradiation data [4] and the on-site measured data is in the order of ±2.5% even for moderate-climate regions like Germany [3]. The study analysed data over 35 meteorological stations in Germany using over 215 complete years (1-14 years per stations between 2005 and 2017) of high quality data.

Over 300 high-quality meteorological stations spread across Europe and Africa are used within 3E's Solar Data validation framework, participating in the continuous improvement of the models. Results of these extensive validations are presented in [2] and validated by [3].

Satellite-based solar irradiance data is evaluated against the reference data from the measurement stations. Hourly, daily, and monthly irradiation for all sites are evaluated by their root mean square error (RMSE), the standard deviation of the error (SDE) and the systematic part of the error (bias).

An overview of the geographical distribution of the error (bias) is shown in Figure 6 and Figure 7 for Europe and South Africa respectively. These validation maps show the yearly difference (bias) between 3E's Solar Data derived from satellite images using advanced CPP models and on-site measured data using high-quality pyranometer measurements collected and maintained by the national weather services of several countries.

As shown in Figure 6, the yearly percentage difference (bias) between 3E's satellite-based solar irradiation data and the on-site measured data is in the order of ±2.5% for many places in Europe. This yearly percentage difference is even lower in some regions across Europe. Results over South Africa show that the yearly percentage difference (bias) between 3E's

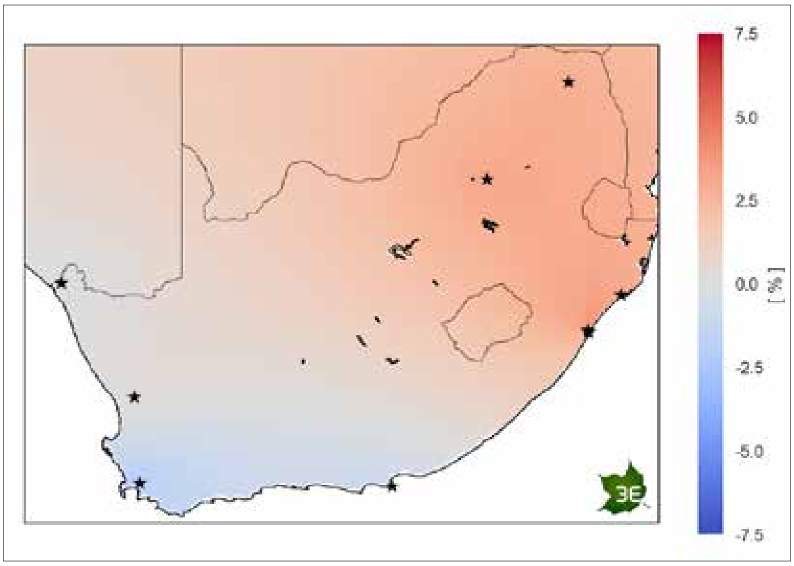

Figure 7: Percentage difference between 3E Solar Data and ground station data measured over one year with high-quality pyranometers maintained by the national public weather services in South Africa

satellite-based solar irradiation data and the on-site measured data is lower in this region of Africa than for many places in Europe, being often around ±2% for the region (Figure 7).

In practice, when computing irradiation by integrating irradiance over long times, random errors are averaged out, decreasing the standard deviation of the error (SDE) while the bias remains the same. As shown in Figure 6 and Figure 7, the systematic component of the error (bias), is on average 2.5%.

Results of the extensive validation show that the random component of the error (SDE) is 10% for daily resolution and 4% for monthly resolution in Europe. Results for South Africa, where hourly data is also available, show that the SDE is around 12%, 6% and 3% for hourly, daily and monthly resolution respectively, showing the clear improvements with other non-physical models. Extended results over multiple years, including hourly, daily and monthly resolution, are presented in [2].

Best practice: combining pyranometer and satellite irradiance data

The strengths of on-site pyranometers and satellite-derived irradiance data sets can be perfectly combined to reduce the uncertainty in both long-term forecasted PV plant yield during the design phase and to detect underperformances during the operational phase. These two data sources are highly complementary and should be used together to obtain redundancy and cross-checks for the most accurate data.

The bankability of a PV project during the design phase can be improved by combining the data of a short period of record, but with site-specific seasonal and diurnal characteristics measured by an on-site pyranometer, with a satellite-based data set having a long period of record, but not necessarily with site-specific characteristics. Upon completion of the measurement campaign (typically around one year), different methodologies can be applied to correlate the measured data at the target site, spanning a relatively short period, and the satellite data, spanning a much longer period. The complete record of satellite data is then used in this relationship to predict the long-term solar resource at the target site. Assuming a strong correlation, the strengths of both data sets are captured and the uncertainty in the long-term estimate can be reduced [7].

Combining pyranometer and satellite-based irradiance data during the operational phase of a PV plant enables robust and advanced statistical analysis in state-of-the-art solar PV plant monitoring software like SynaptiQ [6], which combines both on-site pyranometer and 3E's satellite-derived measurements into validated and precise irradiance data for a specific plant.

Reasons to combine data pyranometer and satellite irradiance data:

- Satellites and pyranometers are fully independent sources of irradiance data that can be compared, analysed and correlated to determine reliable site data.
- For monthly to annual reporting of the overall plant performance by O&M contractors and asset managers, satellite-based data are a reliable source that can be validated by comparison with on-site pyranometer data.
- For long-term yield estimates as computed by investors, installers and consultants, satellite-derived data are a valuable source. Data from a well-maintained on-site solar irradiance monitoring station can be used to further improve the accuracy of the calculations.
- Fault detection and analysis by an O&M contractor requires hourly or even sub-hourly on-site irradiance data. High-quality and well maintained pyranometers are the first choice; satellite data may be used as back-up if the instruments fail or appear to be badly maintained.
- Satellite data may also serve to validate the proper calibration and configuration of pyranometers in case of doubt. For large deviations, cleaning needs or shadowed sensors, satellite data analysis may spare the O&M operator a site visit.

The best practice is to use both on-site pyranometers and satellite data services to obtain accurate irradiance data for solar plant design and performance monitoring over both short and long time-scales. ■

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