Solution 1. Concept

Sensorisation of PV plants for low uncertainty operational data

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List of Acronyms

AC	Alternating Current
AM	Air Mass
B	Normal direct irradiance
DAS	Data Acquisition System
D(0)	Horizontal diffuse irradiance
DC	Direct Current
DET	Deep Experience Team
DT	Digital Twin
DTs	Digital Twins
$\Delta\eta$	Temporal variation of the inverter conversion efficiency
ΔP^*	Temporal vatiation of STC power
ε	Error of the expected in-plane global irradiance
$\bar{\varepsilon}$	Average of ε
η_{INV}	Inverter efficiency
G(0)	Horizontal global irradiance
G(i)	In-plane global irradiance
$G^A(0)$	Actual horizontal global irradiance
$G^A(i)$	Actual in-plane global irradiance
$G^E(i)$	Expected in-plane global irradiance
$G^{eff}(i)$	Effective in-plane irradiance
$G^{eff,A}(i)$	Actual effective in-plane irradiance
$G^{eff,E}(i)$	Expected effective in-plane irradiance

HR	Relative humidity
HV	High Voltage
IAM	Incidence Angle Modifier
I_{DC}	DC current
i.e.	« Id est » (That is)
I_{SC}	Short-circuit current
IES-UPM	Instituto de Energía Solar – Universidad Politécnica de Madrid
KPI	Key Performance Indicator
KPIs	Key Performance Indicators
kW	Kilowatt
kW	Kilowatt hour
LCOE	Levelized Cost Of Energy
LV	Low voltage
MPP	Maximum power point
MPPT	Maximum power point tracking
MW	Megawatt
MW	Megawatt hour
m^2	Square meter
μ_ε	Standard uncertainty of ε
O&M	Operation and Maintenance
*P**	STC power of the PV generator
P_{AC}	AC power
P_{AC}^{A}	Actual AC power

P_{AC}^{E}	Expected AC power
P_{at}	Atmospheric pressure
P_{DC}	DC power
P_{DC}^{A}	Actual DC power
P_{DC}^{E}	Expected DC power
PERC	Passivated Emitter Rear Cell
P_{MPP}	Maximum power point
PR	Performance Ratio
PV	Photovoltaic
PVOP	Project Acronym for project « Digitalising the PV sector for the era of Terawatts »
PVsyst	Photovoltaic system design software
Pyr	Pyranometer
QPV	Qualifying Photovoltaics
σ_{ε}	Standard deviation of ε
SCADA	Supervisory Control And Data Acquisition
SISIFO	Simulation tool to design PV-grid connected plants and PV irrigation systems
STC	Standard Test Conditions
T_{A}	Ambient temperature
T_{C}	Cell temperature
T_{C}^{A}	Actual cell temperature
TC	Transformation Centre
TL	Linke turbidity
TMY	Typical Meteorological Year

V_{DC}	DC voltage
WIHI	Weighted Inverter Health Index
Wp	Watt peak
WP	Work Package

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Keywords list

- PV monitoring
- Sensorisation
- Uncertainty
- PV performance

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1. Executive summary

This document explains in detail the concept at the root of the solutions of WP2, entitled “Sensorisation of PV plants for low uncertainty operational data”, which main objectives are:

1) Go beyond calculating the standard *PR* to include refinements such as temperature correction, consideration of angular and spectral phenomena, or calculation of daily producible energy and actual irradiation gain of the trackers with uncertainty < 1%.

2) Detecting inverter efficiency deviations of less than 0.2%, which would automatically monitor their state of health.

The sensorisation solution proposed in this document combines widely accepted practices (for example, the use of class A pyranometers for measuring global horizontal irradiance) with more advanced ones, suggested by the IES-UPM experience in technical quality control of utility-scale PV plants. In particular:

- Measuring not only global horizontal irradiance but also its direct and diffuse components. That allows for comparing actual and expected in-plane irradiances.

- Using reference modules (not reference cells) for measuring both effective in-plane irradiance (i.e. corrected for spectral, angular and soiling responses) and solar cell temperature. That allows for accurate PV generator STC power characterization.

- Measuring AC power with class 02S energy meters (typically not included in standard inverters). That allows for precise measurements of inverter efficiency.

- Considering spare parts replacement rate as technical quality indicators.

On similar lines, the QPV experience suggests that soiling is often non-uniformly distributed, both within the same PV module and within the same PV array. Intra-module non-uniformity is already considered by the e-Dust (a dedicated soiling measurement equipment developed by QPV). Now, we propose to extend this soiling measurement procedure to a full soiled string, by measuring its I_{SC} and P_{MPP}.

The validation of the solutions proposed and developed is based on a main KPI that is the reduction of uncertainty in a certain variable achieved by its direct measurement with respect to its calculation through mathematical modelling. We plan to carry out two different experiments, respectively, at the IES-UPM outdoor facilities and at a commercial PV plant. The principle of these experiments is to compare actual (directly observed by means of a sensor) with expected (calculated with a model from other previously observed variable) values of a same variable. We foresee two types of experiments: under normal operating conditions and in abnormal operating conditions. Specific target values for uncertainty in hourly values of the links in the PV plant power chain are proposed. These target values correspond to the standard deviation of errors, understood as differences between expected and actual values.

2. Introduction

This report constitutes the first deliverable corresponding to the WP2 of the PVOP project. This WP is entitled "Sensorisation of PV plants for low uncertainty operational data", which main objectives are:

1) Go beyond calculating the standard *PR* to include refinements such as temperature correction, consideration of angular and spectral phenomena, or calculation of daily producible energy and actual irradiation gain of the trackers with uncertainty < 1%.

2) Detecting inverter efficiency deviations of less than 0.2%, which would automatically monitor their state of health.

Recommendations for PV monitoring are available from many years ago[1, 2]. The standard IEC 61724-1 has been updated in 2021 and constitutes a particularly useful reference document. It appropriately states that the objectives of a good PV monitoring include to evaluate the actual performance and to compare with predicted (calculated with a specific performance model, using historical weather data, as, for example, the Typical Meteorological Year, hereafter TMY) and expected values (calculated with a specific performance model, using actual weather data collected at the site). Moreover, a good PV monitoring must allow to detect and localize faults, to help on Operation and Maintenance (hereafter O&M, indicating the best moments for PV module cleaning, anticipating inverter failures, etc.) and to predict the production for some days ahead. Related recommendations are found in subsequent IEC TS 61724-2 and IEC TS 61724-3 Technical Specifications.

All these documents insist on that the evaluation of a PV system requires selecting a specific power model that must be consistent with the one used for the energy yield estimation performed at the beginning of the project.

This (the monitoring objectives and performance modelling) is coherent with applying Digital Twins (hereafter DTs) to PV system, which is on the roots of the PVOP project. The digital twin concept consists of three distinct parts: the real PV system and its operation conditions, the digital representation of the PV system, and the sensors providing the information flow between the real and modelled objects and environments.

The lower the uncertainty of sensors and models, the greater the performance of the Digital Twin. From this, the here proposed sensorization for PVOP DTs derives from a simple criterium: the variables selected to be directly measured are those which experimental values allow reducing the uncertainty in the calculation of some parameters related with performance, in comparison with the use of estimated (not experimental) values. In coherence, the Key Performance Indicators (hereafter, KPIs) proposed for quantifying the advantage of the proposed sensorization are the uncertainty reduction in four relevant points of the power chain: The in-plane global irradiance, $G(\mathrm{i})$; the effective in-plane irradiance, $G^{\mathrm{eff}}(\mathrm{i})$; the Standard Test Conditions (STC) power of the PV generator, P^*; and the inverter conversion efficiency.

[1] Blaesser G and Munro D, "Guidelines for the Assessment of Photovoltaic Plants Document A Photovoltaic System Monitoring", Commission of the European Communities, Joint Research Center, Ispra, Italy, EUR 16338 EN, Issue 4.2 (June) 1993.
[2] Woyte A. et al, "Analytical Monitoring of Grid-connected Photovoltaic Systems: Good practices for Monitoring and Performance Analysis. Report IEA-PVPS T13-03:2014, March 2014.

The PV scene is the most diverse of all the electricity sources, both in sizes (from few kW to thousands of MW), configurations (from small individual to big central inverters) and applications (grid connection, batteries, stand-alone). The here proposed sensorization is for the simple and today best-know case of a PV plant connected to the grid without batteries. Moreover, it to the highest quality monitoring we can imagine, allowing for detecting even slight deviations between expected and actual characteristics and performance. Extension to other different or less demanding cases are let for further PVOP steps, once we gain practical experience with this first case.

3. PVOP sensorisation proposal

3.1. Conceptual aspects

The sensorisation kit proposed in this document, intended for application in PVOP DTs, combines widely accepted practices (for example, the use of class A pyranometers for measuring global horizontal irradiance) with more advanced ones, suggested by the IES-UPM experience in technical quality control of utility-scale PV plants (a representative example is given in annex). In particular:

- Measuring not only global horizontal irradiance but also its direct and diffuse components. That allows for comparing actual and expected in-plane irradiances which, in turns, allows for detecting deviations (actual versus predicted) of the position of the PV generators, and for correcting readings of irradiance sensors with different positions, as typically found in sloping terrains.

- Using reference modules (not reference cells) for measuring both effective in-plane irradiance (i.e. corrected for spectral, angular and soiling responses) and solar cell temperature. That allows for accurate PV generator STC power characterization, which opens the door for automatic degradation estimations. Measuring DC currents in such a way that reverse currents, resulting from possible isolation faults in the PV generator (modules, wires and connection box) could be detected in good time to prevent major damage, namely fires in the PV generator.

- Measuring AC power with class 02S energy meters (typically not included in standard inverters). That allows for precise measurements of inverter efficiency which, in turns, allows for detecting inverter malfunctions. For example, due to excess dust in the cooling air filters.

- Considering spare parts replacement rate as technical quality indicators. For example, the blown fuses rate talks about the quality of the DC wiring of the PV generators. Hence, information about the replacement of fuses from O&M records, must be incorporated to the DT and systematically analysed.

On similar lines, the QPV experience suggests that soiling is often non-uniformly distributed, both within the same PV module and within the same PV array. It is well known that non-uniformity translates into additional mismatch losses. Intra-module non-uniformity is already considered by the e-Dust (a dedicated soiling measurement equipment developed by QPV) by measuring not only the I_{SC} but also the P_{MPP} of a soiled and of a clean module. Now, we propose to extend this soiling measurement procedure to a full soiled string, by measuring its I_{SC} and P_{MPP}. To avoid formation of hot-spots due to short-circuits, measurement process is performed during short periods of time. For example, a soiling value can be obtained for each 10 minutes period, but the measurement itself is taken in less than 10 ms. During the rest of time, the string can be reconnected to the PV array thus avoiding energy losses.

For presentation purposes, we will pay attention to the power chain from the horizontal irradiance to AC output of the PV plant. That is:

$$G(0) \rightarrow G(\mathrm{i}) \rightarrow G^{\mathrm{eff}}(\mathrm{i}) \rightarrow P_{DC} \rightarrow P_{AC}$$

where $G(0)$ is the horizontal global irradiance, $G(i)$ is the in-plane global irradiance, $G^{eff}(i)$ is the effective in-plane global irradiance, P_{DC} is the DC power at the inverter input, and P_{AC} is the AC output of the PV plant. Inspired by this chain, the selected variables to be sensorised have been classified into four different categories: Weather, operation conditions, DC response and AC response.

Figure 1 shows (in blue) the most extended situation in today PV plants. Superscript "A" means actual, "Pyr" means measured by a pyranometer, "inverter" means directly given by the inverter. T_A, HR and P_{at}, respectively, means ambient temperature, relative humidity and atmospheric pressure. "Meteo station" means that these last variables are measured by a standard meteorological station. The evaluation of the PV plant behaviour is mainly accomplished by comparing long-term (typically yearly, or monthly) integrals of actual and predicted values. Note that the widely used PR is simply the ratio between the sum of the P_{AC} readings to the sum of the $G(i)$ readings. $G(0)$ readings are used to analyse the representativeness of the Typical Meteorological Year. Other meteorological variables are none or scarcely used.

	Weather	Operation conditions	DC response	AC response
Often today: Comparison with annual predicted	$G^A(0)$ Pyr	$G^A(i)$ Pyr	P^A_{DC} Inverter	P^A_{AC} Inverter
	T_A, HR, P_{at} Meteo station			

Figure 1. Most extended monitoring solution in today commercial PV plants. Horizontal and in-plane irradiations are given by pyranometers. DC and AC power are directly given by the inverters.

Figure 2 shows (in red) what need to be added to create a DT as here proposed. New variables to be measured appear [B and $D(0)$, respectively, meaning normal direct and horizontal diffuse irradiances; $G^{eff}(i)$ measured by a reference module, which also measures the solar cell temperature, T_C^A; arrows represent calculations leading to expected values, signaled by the superscript "E". Note that now, the actual irradiances and power values can be compared with corresponding expected ones, which provide the key for detecting both equipment malfunctions and modelling errors. Besides, new variables associated to the inverter behavior are now considered: the efficiency, η_{INV}, and an index associated to its state of health, WIHI.

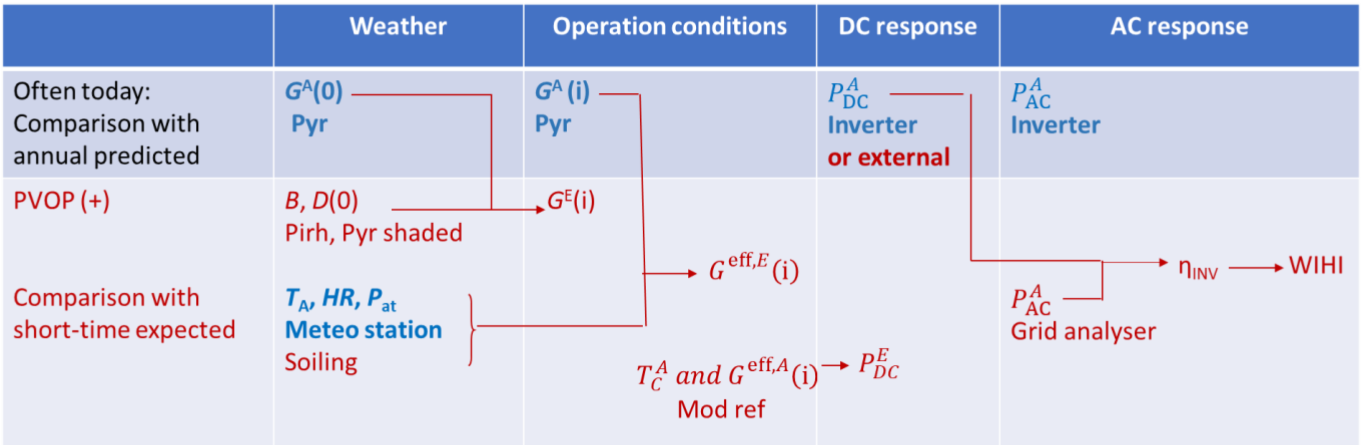

Figure 2. Additions required for creating a PVOP digital twin. New variables to be measured appear [*B* and *D*(0), respectively, meaning normal direct and horizontal diffuse irradiances; G^{eff}(i) measured by a reference module, which also measure the solar cell temperature, T_C^A; arrows represent calculations leading to expected values, signaled by the subscript "E".

Every new thing sparks controversy, so PVOP must pay attention to elucidate the pros and cons of the new sensors with respect to the most extended monitoring solution in today commercial PV plants. Namely, the sensors for decomposing the horizontal irradiance, for the operation conditions, and for the AC power; respectively, pyrheliometers and shaded pyranometers, reference modules and grid analysers. In these lines, section 2.2 gives more details about variables, sensors, and the purpose of the derived calculations in the context of DTs.

Besides, it is proposed to gain experience with two DTs related experiments performed in the PVOP framework. That must provide the basis for estimating the KPIs proposed for quantifying the advantages of a proposed sensor. They are described in section 2.3.

3.2. More in detail

Tables 1 to 4 provide, respectively, for weather, operation conditions, DC response and AC response, details on the purpose of the measured values and related calculations. Technical requirements of the sensors (operating margins, accuracies, etc.) can be found in IEC 61724-1 and IEA-PVPS T13-03:2014 and are dispensed here. Instead, comments on its usefulness in practice, generally inspired by previous IES-UPM experience, are given.

Variable	Sensor	General purpose	Input for modelling of expected
Global Horizontal Irradiance, *G*(0).	Pyranometer. Spectral pyranometers.	Comparing with TMY. Spectral irradiance correction.	In-plane irradiance, $G^E(\mathrm{i})$.
Ambient temperature, T_A.	Pt100 or Pt1000.	Comparing with TMY.	Solar cell temperature, T_C.
Relative humidity.	Capacitive.		Spectral irradiance correction.
Wind speed and direction.	Anemometer and vane.	Comparing with TMY. Tracking safety positions.	Solar cell temperature, T_C.
Atmospheric pressure.	Piezoelectric.	AM calculation.	Spectral irradiance correction.
Hail.	Hail detectors.	Tracking safety positions.	

Table 1. Weather variables related to PVOP DTs.

Large PV plants often have a conventional meteorological station that includes most of the elements listed in this table, although some of them are not used in current evaluation procedures, so that corresponding data are not used for anything. However, they can be interesting for more advanced evaluation procedures, like the DTs developed in PVOP. This is the case of the relative humidity and of the atmospheric pressure. They are not used today, but they can be useful for estimation of the spectral correction factor applied to the global irradiance for deducing the effective one. It is opportune remember that spectral losses can represent up to 3% of energy production in some regions. In this sense, it is interesting to note that new "spectral radiometers" have recently appeared on the market. Such equipment is specifically designed for giving the atmospheric parameters that are relevant for the spectral response (Air Mass, Aerosols Optical Depth and precipitable water) and even the spectral correction factors for different PV solar cell technologies. We think it is of interest to study and gain experience with this new instrumentation that seems suitable to improve PV modelling.

On the other hand, weather extreme events are receiving growing attention. For example, hail sensors triggering the tracker to adopt a very tilted position for reducing hail damage on the PV modules are being increasingly used.

Variable	Sensor	General purpose	Input for modelling of expected
Direct and Diffuse irradiance components, *B* and *D*(0).	A pyrheliometer and a pyranometer shaded by an automatically tracked shadow ball, or only a pyranometer shaded by a manually adjusted shadow ring.	Redundance for reducing uncertainty in *G*(0). Translation from horizontal to in-plane irradiance. Sky categorization for position irradiance corrections, and PV module degradation estimation.	Global in-plane irradiance, $G^{E}(\mathrm{i})$. Linke turbidity, *TL*.
Global In-plane Irradiance, *G*(i)	Pyranometer.		Effective in-plane irradiance, $G^{\mathrm{eff},E}(\mathrm{i})$.
Soiling ratio.	Soiled PV modules and strings versus a clean PV module.		Effective in-plane irradiance, $G^{\mathrm{eff},E}(\mathrm{i})$.
Effective in-plane irradiance, G^{eff}(i).	Reference module.		DC power, P_{DC}^{E}.
Solar cell temperature, T_C.	Reference module.		DC power, P_{DC}^{E}.

Table 2. Operation conditions variables related to PVOP DTs.

Related comments are:

The decomposition of global horizontal irradiance in its direct and diffuse components is a classic topic of solar engineering, and satisfactory models are available to address the most conventional issues, such as the construction of TMY for baseline case designs, estimation of yearly and monthly irradiation tracking gains, etc. However, the value of these models is doubtful when it comes to new problems arising in the PV plant scenario. For example, in large PV plants deployed on non-flat terrain, the problem arises of correcting the irradiance measurements on surfaces where there are sensors to estimate the irradiance corresponding to other surfaces where there are not. This is relevant for performance and soiling estimations and must be solved with uncertainties as low as 1%, which are likely out of today available modelling, so that the use of dedicated instruments for direct measurement of the irradiation components must be considered.

In practice, the instrumentation for decomposing the horizontal irradiance can adopt two alternatives. The highest quality, but also the most expensive one, consists of using both a pyrheliometer for measuring the direct irradiance, and a pyranometer shaded by a shadow ball for measuring horizontal diffuse irradiance, mounted on a fully automatic tracking device for keeping the pyrheliometer and the shadow ball pointed to the Sun. It offers accuracy and redundancy advantages, but its additional cost (in comparison with a conventional meteorological station) is about

50 k€, and its proper functioning requires often cleaning, because the pyrheliometer is very sensitive to soiling. A simpler and cheaper alternative consist of using just a pyranometer with a shadow band. It is less accurate (the direct irradiance is not directly measured, and the diffuse irradiance readings need to be corrected for the portion of the sky hidden by the band), but its additional cost is about 5 k€ and the required manual band adjustments can be done about once per week.

On the other hand, modelling the operation conditions from weather data raises suspicious of uncertainty. For example, modelling effective from global in-plane irradiance requires correcting for the angular, soiling and spectral responses of the concerned PV plant modules. But the corresponding PVsyst models are likely inadequate for that. Its IAM (angular) model does not consider the angular effects of soiling, for which there is large experimental evidence, and its spectral model only consider the effect of the Air Mass, disregarding the effects of the diffuse/global ratio and of the relative humidity. Measuring these operation conditions with reference modules is the most accurate alternative but requires facing some inconvenient related to the practical handling of these modules: they are much bigger than pyranometers or reference cells, and they are not object of a standard commercial procedures.

Variable	Sensor	General purpose	Input for modelling of expected
Inverter operating status (MPPT, clipping, limited by the grid operator…..).		Estimating the working point (V,I) of the PV generator.	DC power, P_{DC}^{E}. AC power, P_{AC}^{E}.
DC current, I_{DC}.	At least, one for each 30 strings.	Estimating actual performance. Detecting string loss. Detecting inverse current.	
DC voltage, V_{DC}.	At the true inverter entry.		
DC power, P_{DC}.	Reference module.		AC power, P_{AC}^{E}.

Table 3. DC response variables related to PVOP DTs.

DC surveillance granularity is an open question, and a wide range of solutions coexist in current PV market. Current measurement of each individual string has been often implemented in DC string boxes. However, the in-field experience raised suspicions about the real usefulness of such detailed measurement. In many cases, string loss alarms were caused more by failures in the measurement equipment than by failures in the string themselves. On the opposite, central inverters, which DC input can receive tens of strings in parallel, often measure only the total DC current, which is needed for the inverter to search the MPP but does not allow for detecting the loss of a string. Recently, so called “string inverters” include a measurement for each MPP entry which, in turns, can be constituted by the parallel of few strings. The IES-UPM experience is mainly related with central inverters and suggests that one current measurement for each 30 strings suffices for detecting the loss of only one string, and that early detection of reverse current is important to prevent damages in the PV field, in case of electric arcs and some ground isolation faults.

Inverters use to give DC voltage values. To properly calculate the inverter efficiency, attention must be paid to assure this value is taken just at the inverter entry (not at any other internal point), to account for losses in internal protections and so on.

Variable	Sensor	General purpose	Input for modelling of expected
Active power.	Grid analyser.	Measuring output energy. Estimating actual inverter efficiency.	Power delivered in high voltage.
Reactive power.	Grid analyser.		
Cos φ.	Grid analyser.		

Table 4. LV AC response variables related to PVOP DTs.

Power measurements directly given by the inverter are often unsatisfactory. Subsequent efficiency calculations sometimes lead even to results lacking physical meaning (greater than one values and so on). Together with a certain reluctance of inverter manufacturers towards in-field independent testing, that has fostered the idea that efficiency cannot be measured in the field. However, after a large related experience, we think that poor inverter measurements are rooted in inadequate cosφ measurements, and that is overcome just using a grid analyser (i.e., a standard energy meter) for measuring AC power. It is important mentioning that routine efficiency measurements are the base for calculation the WIHI (Weighted Inverter Health Index), an electrical signature proposed by the IES-UPM to daily quantify the inverter health. We think that this index potentially allows detecting efficiency losses as low as 0.2% which, in turns, opens the door for automatic maintenance (cleaning filters, etc.) recommendations.

Finally, PV monitoring is widely understood as the routine observation of parameters directly linked to the energy flow, from input irradiance to output power. However, we propose to also routinely considering other data, like spare parts replacement rates as technical quality indicators. For example, some experiences with commercial PV plants (presented at the kick-off PVOP meeting) suggest that the DC fuses blowing rate can be a good indicator of DC wiring quality, so that isolation faults, which represent a main cause of failures and energy losses, can be somewhat anticipated.

4. Experiments and KPIs

It is proposed to gain experience with two DT related experiments performed in the PVOP framework. That must provide the basis for estimating the KPIs proposed for quantifying the advantages of a proposed sensor. As mentioned above, the basis for this is the reduction of uncertainty in a certain variable achieved by its direct measurement with respect to its calculation through mathematical modelling. Seeking to shed light on this issue and, and the same time, to gain experience in DTs, we plan to carry out two different experiments, respectively, at the IES-UPM outdoor facilities and at a commercial PV plant. In both cases, the experiment will use an already existing PV system routinely injecting energy to the grid. Required sensors and Data Acquisition System (DAS) for implementing the corresponding DTs will be added.

The principle of these experiments is to compare actual (directly observed by means of a sensor) with expected (calculated with a model from other previously observed variable) values of a same variable. We foresee two types of experiments.

4.1. Under normal operating conditions

First, the PV plant is operated in normal conditions (i.e. without any malfunction or failure). The two main objectives are, on the one hand, selecting the more adequate instrumentation for the real PV system and, in the other hand, selecting the models for its digital representation in the DT. In this sense, it is opportune remembering that the current angular and spectral PVsyst models are likely inappropriate, so that other alternatives must be explored. Fortunately, the open literature includes some appealing propositions that can help on this task.

For example, the in-plane effective irradiance as given by a reference module, $G^{eff,A}(i)$, faces the calculated from the the in-plane effective irradiance as given by a standard pyranometer with an angular and spectral model, $G^{eff,E}(i)$. Foreseeably, plotting the corresponding error, ε, understood as ε= $G^{eff,E}(i)$ - $G^{eff,A}(i)$,, will result in a cloud of points that can be characterized by an average, $\bar{\varepsilon}$, and a standard deviation, σ_ε. Then the associated standard uncertainty is given by $\mu_\varepsilon = (\bar{\varepsilon}^2 + {\sigma_\varepsilon}^2)^{1/2}$. That can be also made substituting the reference module by a spectral pyranometer. Then, only an angular model must be added. Finally, if μ_ε is lower than a certain threshold, the use of the sensor is definitively recommended and the corresponding KPI is given by $2\mu_\varepsilon$, i.e., by the expanded uncertainty reduction.

Note that μ_ε depends on both the model for calculating the expected value and the sensor for measuring the actual value. Hence, the result of the experiment will consist of a double entry table given the μ_ε value for each model-sensor combination. The experiment must be kept on-going during about at least six months to cover all positions of the Sun in the sky.

4.2. In abnormal operating conditions

The experiments will consist of imposing malfunctions (inaccurate searching of the MPP, significant soiling, etc.) and failures (stop of tracking motion, fuse blowing, etc.), and observe the DT reaction: if it is able to detect the malfunction and in how much time. The imposed failures must be representative of what happens in the reality of commercial PV plants. The PVOP DET (Deep Experience Team) will have a crucial role in defining and prioritizing the list of considered failures. As a matter of example, the Annex presents a real case of low tracking irradiation gain, suggested by the IES-UPM experience. A DTE brainstorm exercise, currently in progress, should add other problems to the list.

4.3. At the IES-UPM outdoor facilities

Two PV generators, one monofacial and other bifacial, with respective peak powers of 5 kW and 13 kW. A wide collection of irradiance sensors (pyranometers, pyrheliometer, reference modules, etc.) are already available. In relation with the decomposition of the incident irradiance in its direct and diffuse components, there is a pyrheliometer for measuring the direct irradiance but neither pyranometers combined with shadow devices for measuring the diffuse irradiance nor recently available spectral pyranometers.

In order to implement DTs for the above-described PV systems, and to further study the convenience of the sensorization alternatives for decomposing the incident irradiance, it is necessary to add two pyranometers (one with a shadow band and the other with a shadow ball), a spectral pyranometer, an equipment for measuring soiling at one module and also at one string level, and a Supervisory Control And Data Acquisition (SCADA) able of supporting the DT models.

4.4. At a commercial PV plant

Looking for implementation of a first PVOP DT in a commercial PV plant, it is preferable that it is a large plant (> 10 MW) composed by one-axis trackers (the most attractive solution in terms of LCOE , and that is not available in the outdoor testing IES-UPM facilities), relatively close to Madrid (to facilitate direct observations and complementary measurements that helps to carefully evaluate the plant operational behaviour) and owned and operated by open-minded people who are interested in innovation and does not put many obstacles for fear of confidentiality issues.

Likely, that will require selecting a particular generator-inverter unit for the DT implementation, adding (if not existing) a pyranometer and a reference module for direct in-plane global and effective irradiances, a pyranometer with a shadow band (the more complex alternative of using a pyrheliometer together with a pyranometer and a shadow ball can, in principle, be avoided here and only analysed in the IES-UPM experiment) and a spectral pyranometer.

An initial round of tentative contacts has given a first candidate. A 39 MW PV plant located in Zamora province (Castilla León, Spain), about 220 km far from Madrid. It is composed by 5 TC (transformation Centers), each formed by a LV/HV transformer and two 3 MW central inverters. PV modules are monofacial, PERC, half-cell, with peak power of 660Wp. PV arrays are mounted on one-axis trackers. The SCADA has been provided by QPV, who also performed the tests at the beginning of the plant operation, which ensures a depth knowledge of the PV plant characteristics, and is in charge of the routinary evaluation of the PV plant functioning.

4.5. Targets for KPIs

Table 5 presents our estimation for uncertainty in hourly values of the links in the PV plant power chain. In principle, one hour is an adequate lapse for PV system DTs. Note these values correspond to the standard deviation of errors, understood as differences between expected and actual values. The upper line corresponds to a today common PV plant (instrumentation restricted to two pyranometers for *G*(0) and *G*(i), respectively, internal to inverter DC and AC power meters, and expected values calculated with the same PVsyst models used for the energy yield assessment performed before the project set-up). The lower line is our proposition to achieve the following targets for the KPIs in this WP2.

	***G*(0)**	***G*(i)**	**G^{eff}(i)**	**P_{DC}**	**P_{AC}**
Common today	N.A.	2	2	2 - 3.5	2
PVOP target	N.A.	0.5 $G_t(i)/G_t(0)$ 1	0.5	0.5 ΔP^* 0.5	0.5 $\Delta\eta$ 0.2

Table 5. Standard uncertainties in hourly averages values of the relevant links in the power chain for (upper line) what is common in today PV plants and (bottom line) what is targeted in PVOP. Values are given in %. It is worth remembering that the commonly used "expanded" uncertainty is twice the "standard" uncertainty.

It must be considered that these links are not directly involved in anomalies detection. For that, other derived parameters, often called "electrical signatures" are required. The table includes three: the irradiation gain[3], [$G_t(i)/G_t(0)$], that gives clues for detecting failures in the position of the PV arrays; the temporal variation of STC power, ΔP^*, that allows for estimating PV array degradation; and the temporal variation of the inverter conversion efficiency, $\Delta\eta$, that allow for estimating the inverter state of health.

3 Subscript "t" means "irradiation in a period of time t" (integral of the irradiance).

5. Conclusions

This report is the first PVOP deliverable. It is intended to analyse the sensorisation required for developing PV systems Digital Twins with high evaluation and anomaly detection capabilities. It is opportune remembering that such DTs essentially compare actual (measured) with expected (calculated) values for different related performance parameters (irradiance, power…).

Regarding the state-of-art of PV system monitoring, some novelties are proposed. Namely:

- Measuring not only global radiation but also its direct and diffuses components.
- Using reference modules for measuring both the effective in-plane irradiance and the solar cell operation temperature.
- Measuring DC currents in such a way that inverse current could be quickly detected.
- Measuring AC power by means of grid analysers.
- Consider spare parts replacement rates as an indicator of technical quality.

This report paves the way for next PVOP experimental steps, that must lead to develop effective PV systems DTs. For that, two experiments performed, respectively, at the IES-UPM outdoor testing facilities and at a commercial PV plant are proposed. Corresponding KPIs based on the uncertainty level derived from comparing actual and expected values are proposed. These KPIs should provide the basis for, first, deciding whether or not is convenient to use a certain sensor and, second, quantify the improvement associated to its use.

Annex. A selected case from the IES-UPM experience: the irradiation gains of real one-axis tracking

The underlying intention of presenting this example here is to show, on the one hand, that the careful analysis of PV plants operating data allow to reveal problems that go officially undetected in the current state-of-art and, on the other hand, that PV performance modelling still has room to improve. This is fully in coherence with PVOP lines.

Table A1 compares, in yearly terms, the predicted (modelled from the TMY data) and the actual irradiation values recorded in a commercial PV plant with one-axis horizontal trackers and monofacial modules (other details allowing the identification of the plant are confidential). Opportune comments are:

- The tracker irradiation gain (in-plane/horizontal, both global) is 12% below predictions [(31.5 -35.8)/35.8 = -0.12]. Corresponding in-plane irradiation loss is about 3%; being the main reason for underperformance (regarding predictions) in this plant.
- IES-UPM conversations with relevant PV market players suggest this is a widespread problem in current PV scenario. Even more, some players suggest that 5% of global in-plane irradiation loss is likely below the average.
- Despite its relevance, such loss goes undetected to *PR* and availability, which are the two main parameters regulating current O&M contracts. That helps to understand why, despite its relevance in practice, this problem is rarely mentioned in the open literature.

Variable	Predicted (P)	Actual (A)	Difference (%) (A-P)/P	Comment
Horizontal irradiation (kWh/m^2)	2237	2262.5	+0.8	The TMY is very representative in terms of *G*.
In-plane global irradiation (kWh/m^2)	3039 (+35.8%)	2975.3 (+31.5%)	-2.1	The irradiation gain is significantly lower than predicted.
In-plane effective irradiation (kWh/m^2)	2878 (-5.3%)	2907.8 (-2.3%)	+1	The PV plant environment is not prone to dirt.
DC Energy (MWh p.u.)				

Table 6. Components of predicted and actual radiation related variables, observed along a year in a large PV plant. Other links of the power chain (DC Energy…) are not relevant here.

Faced to the study of this problem, the IES-UPM postulate, as a first possible reason, that the actual position (i.e. the tracker rotating angle) deviates from predicted. It is worth commenting that subsequent analysis is made difficult by the fact that the SCADA does not provide information about the predicted position (again, this is generalized in current SCADAs). Instead, it records the so called “target” position, which is of no help, because it is directly given by the tracker controller, so that it incorporates possible position modifications made by the tracker manufacturer for whatever reason. The pattern of shadows observed on the ground represents an interesting clue.

Figure 3 shows that predicted positions during back-tracking period led to a fully shaded ground while more lying ones give appearance to bands of light. It must be recognized that the predicted positions are calculated for a hypothetical perfectly flat ground. However, real grounds always show some degree of roughness, as seen in Figure 4 (picture taken at the same plant of Table 6). And it happens that this roughness has impacts on the mutual shading between the different tracker rows, that manifest themselves in non-linearities in the light bands seen in the ground during the back-tracking time, as can be seen in Figure 5 (again, picture taken in the same plant that Table 6).

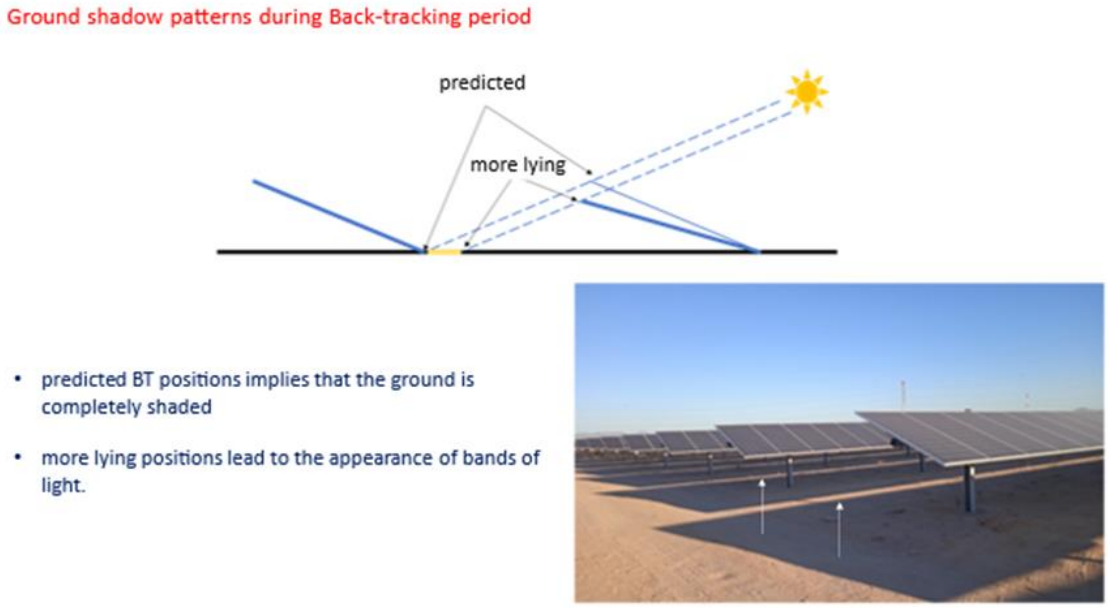

Figure 3. A1. Ground shadow patterns during back-tracking period

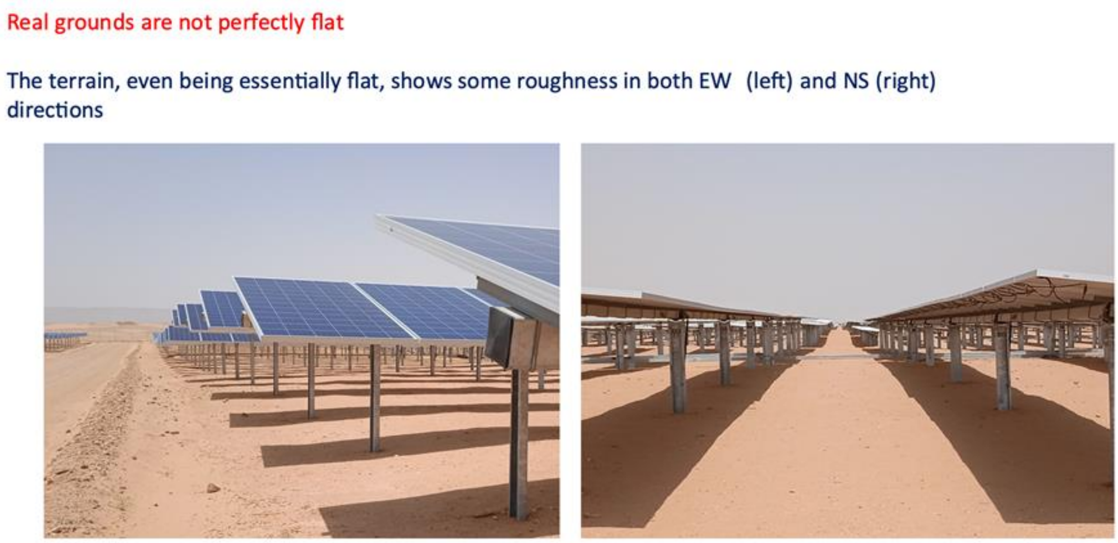

Figure 4. A2. Roughness of terrain at real PV installations

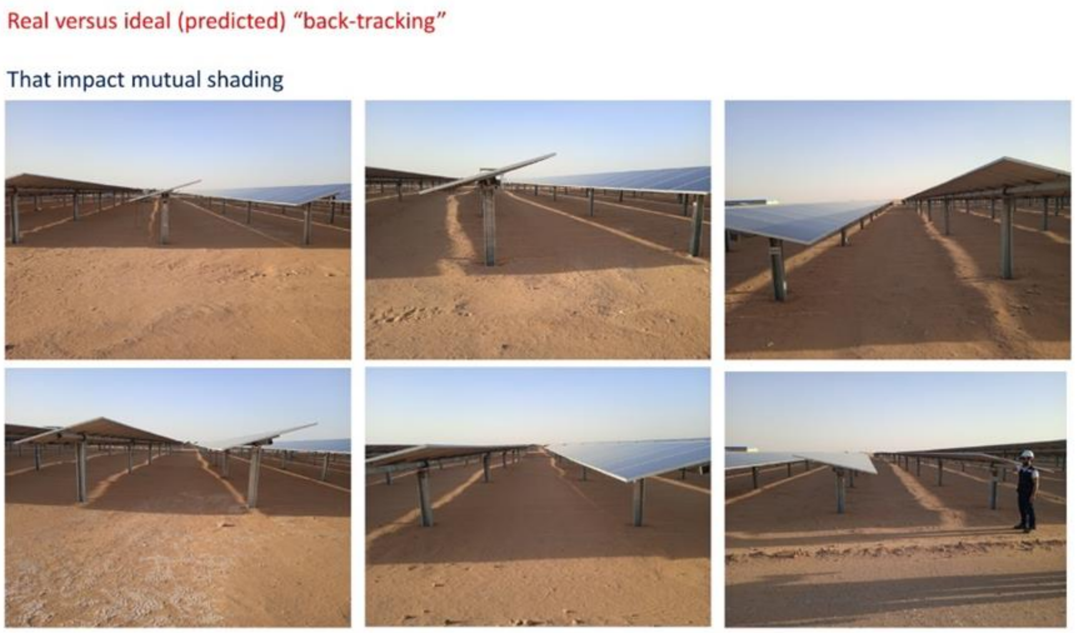

Figure 5. A3. Different ground shadow patterns observed at a real PV plant

With this in mind, we postulate that, to avoid mutual shading during back-tracking and to compensate for step-to-step movement, the racker controller orders more lying positions than those predicted for completely flat terrain. Figure 6 shows the evolution of both the real (recorded at the SCADA) and the predicted (calculated by us) positions along a representative day. A deviation of up to 7 degrees in observed at the beginning of the day, which progressively reduces along the back-tracking time. On the other hand, significant deviation is not observed during normal tracking time. Then, we have simulated the energy yield of this plant without and with the observed deviation (is opportune mentioned that this cannot be made with current PVsyst) using SISIFO, an open-source PV simulation software developed by the IES-UPM, and the TMY of the site. Figure 7 shows the corresponding result which leads to an irradiation loss of about 3%, as observed at the starting of the analysis exercise.

A sound interpretation of this case is that the apparent underperformance is not such. What really happens is that the model used for prediction (based on the assumption of perfectly flat terrain) is not accurate. It is somewhat shocking realizing that this situation could have been detected and diagnosed from the beginning of the PV plant operation, because actual tracker positions are recorded at the SCADA from then, and the calculation of the predicted positions is rather straightforward. However, the situation remained undetected during about three years, until the IES-UPM inspection. That shows there is room for improving the current evaluation procedures, mainly based on *PR* and availability.

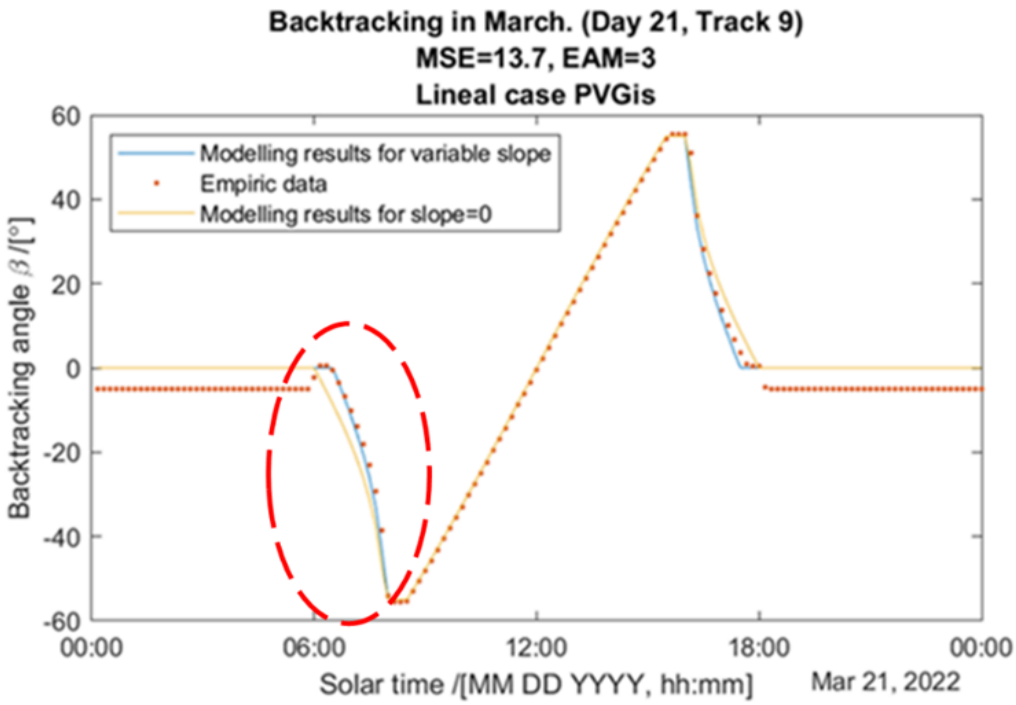

Figure 6. A4. Evolution of both the real (recorded at the SCADA) and the predicted (calculated) tracker rotating angle along a representative day

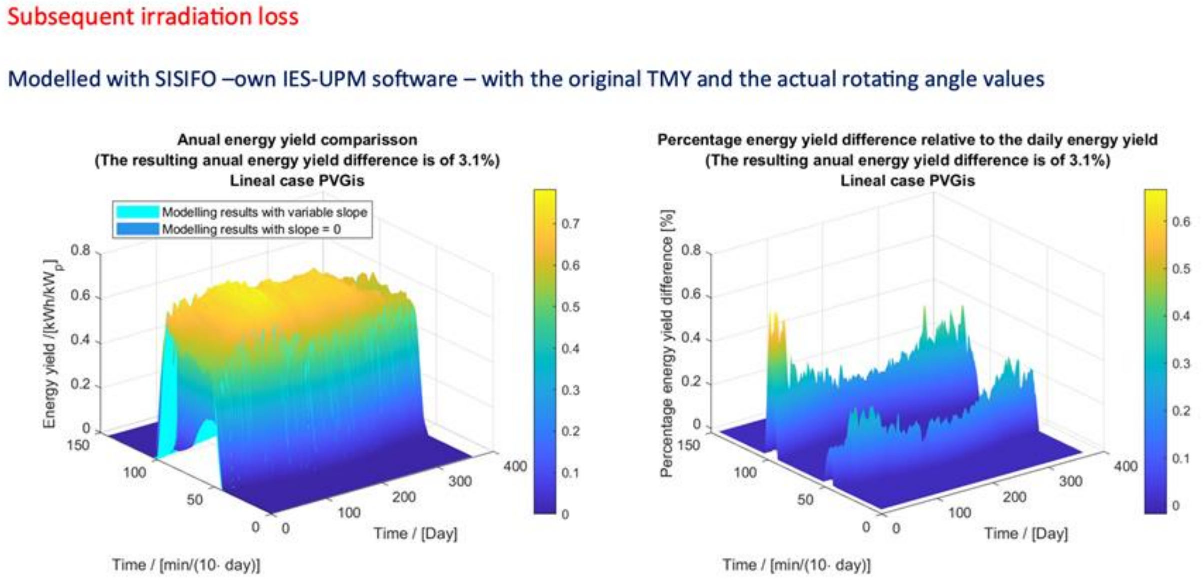

Figure 7. A5. Energy yield simulation of the PV plant considered without and with the observed deviation