Solution 5. Concept

Near 100% automatic and predictive PV asset management software to maximise performance and optimisation of asset O&M management based on multi-level KPIs

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List of Acronyms

ISOH	Inverter Weighted Health Index (ISOH)
DET	Deep experienced team
PERC	Passivated Emitter and Rear Cell
OPEX	Operational expenditure
O&M	Operating and Maintenance
PMT	Performance Monitoring teams
SEI	Stakeholders of the European Industry

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Keywords list

- Performance optimization
- Key Performance Indicators
- Decision tree
- Asset management

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1. Executive summary

This document presents the concept that supports the solutions under the WP5, entitled “Management software of PV Assets to maximize performance”, which main objectives are to develop new methodologies, procedures and strategies to improve the management of photovoltaic (PV) fleets and allow optimizing their performance at portfolio level.

To create a manageable and useful system of indicators, the concept focuses first on deciding which process, variables set and analysis path would be the most efficient and comfortable for monitoring a certain problem. For settling a general structure for dealing with those processes, a decision tree logic is proposed. The objective of the decision tree will be to simulate the exercise of any operator of a performance monitoring team (PMT) who must manage a portfolio and who daily asks him/herself: are all my PV plants performing correctly? If there is something wrong, the decision tree should allow identifying the problem, making the diagnostics, quantifying the related losses and providing the solutions or corrections to make. So, the decision tree should follow a certain order of questions: which PV plant is not working well? Within that plant, what element is failing? Why is it failing? Do all elements of that type fail or only specific ones? In the second case, which of them? How much energy is being lost due to the anomaly? Which level of priority does its resolution has? How can it be solved? How the resolution procedure should be activated and when?

In order to proceed through that decision path, the corresponding families of indicators will be created to allow the PMT operator to solve, at a glance, the test at each node. The analysis should finish with providing a clear diagnostic of the case and an intervention protocol to solve it.

The general idea is to work with KPIs at different levels, where high-level indicators will encompass or consolidate the information given by low-level ones. This approach allows a PMT operator to gain a comprehensive yet concise understanding of the status of a PV asset by examining a single, high-level index (just one number), rather than having to engage with numerous indicators. Such unique indicator will be referred to as ‘State of Health Index’ of the PV plant and will incorporate all the information of the asset performance, therefore giving a much more detailed vision of the state of the installation than a single PR or than the contractual parameters.

The implementation of the solution will be validated to guarantee the correct performance of the algorithms and to quantify its benefits. For this purpose, this document presents a set of tests in a real environment and a set of KPIs to evaluate its performance.

2. Introduction

This report presents the starting point of Work Package 5 (WP5) of the PVOP project. WP5 is entitled "Management software of PV Assets to maximize performance", which main objectives are to develop new methodologies, procedures and strategies to improve the management of photovoltaic (PV) fleets and allow optimizing their performance at portfolio level.

The main challenges that PV plants owners or operators face when it comes to properly managing their assets and optimizing their return include:

- OPEX optimization. Increasingly demanding cost and margin scenarios, coming from increasingly competitive energy prices put additional pressure on cost optimization, leading to adjustments in the budgets available for O&M and Asset Management.

- The management of progressively larger asset portfolios. The number of PV plants is increasing exponentially and their growing development prospect in the context of the Energy Transition is causing most of the actors in the sector to redouble their commitment to the promotion of new installations. Furthermore, the average size of PV plants is growing (the current standard are plants between 50 MW and 100 MW, but it is common to find installations of 300-500 MW, or even above 1 GW). This portfolio growth is a challenge as it implies the growth of the management team and the incorporation of trained and expert profiles, which is not easy given the demand rates in the sector. In fact, the lack of expert profiles and the difficulties to incorporate trained personnel has been identified as one of the major threats the sector will face to meet the EU targets (Reuters, 2023).

- The necessity to analyse immense amounts of data. As a direct consequence of the previous point, the amount of information generated by PV plant is increasing (millions of data per day). Optimizing the operation of assets requires an agile and detailed analysis of all this data, which is unaffordable with manual calculations or semi-automatic tools, like Excel sheets. Furthermore, dealing with data always entail data preparation, cleaning and validation before even starting to analyse it. As data volumes continue to grow, these tasks become increasingly time-consuming, underscoring the need for automated tools to streamline the process. In fact, according to internal sources from the sector, a significant share of time of the performance monitoring teams (PMT) is dedicated to these tasks, limiting their analysis capabilities.

- The management of portfolios with increasingly delocalized and heterogeneous assets: the globalization of companies in the sector and their ability to operate in different markets means that portfolios are made up of widespread installations located in different countries (and even continents); subject to multiple climate types, each of them with its own characteristics and implying particular challenges; different latitudes (meaning different behaviour of the PV plants), different time zones (implying logistics issues); connected to different electrical networks (implying particular grid restrictions, operating codes, market characteristics…). Furthermore, the PV plants themselves can be very different own from each other, not only as different locations stand for different designs (for example, installing one-axis horizontal trackers is highly suitable for low latitudes but does not make sense for high latitudes), but also as technology is evolving very quickly and a stable paradigm in design is far from being achieved. For example, PV modules' technology standards have gone from polycrystalline to monocrystalline silicon, then to PERC, bifacial modules, half-cut cells, N-type cells… This rapid evolution has been accompanied by very significant changes in the manufacturing processes what, in turn, implies different arising problems or anomalies to be looked for in the field. This process has occurred also at inverter, structure, terrain levels, what adds further complexity. All this heterogeneity makes it difficult to standardize the analysis and compare plants based on common parameters, which prevents their optimization. Finally, these portfolios are usually managed from centralized headquarters from which it is not always straightforward to understand the nature of the issues coming from the field.

- The need to integrate data from supporting technologies. As PV plants evolve to more competitive scenarios, the need for better market incorporation, performance optimization and O&M cost reduction drive to the integration of complementary technologies, such as thermography inspections, I-V curve testing campaigns, degradation tests, weather prediction, energy management strategies... The integration of different types of information becomes crucial to have a unique and optimized decision system.

- The need to remotely manage and evaluate O&M teams in the field to achieve asset optimization. This issue is of significant importance yet is often given insufficient attention. Operational failures minimization needs for quick acknowledge times, but also for low response and resolution times (Europe, 2019), what depends basically on the capabilities and the performance of onsite teams. Controlling, evaluating and motivating these teams for an optimized work development is not straightforward from remote headquarters, given distance, time zone differences, protocol misalignments or even cultural differences.

2.1. Automatic analysis tools

The use of automatic and advanced analysis tools for the operation of PV plants helps solving several of these challenges, since they allow:

- To manage large amounts of data in an orderly, systematic, quick, automatic and homogeneous manner.

- To automate analysis, reduce working times and eliminate manual tasks. Additionally, they minimize human errors when performing analyses.

- To increase the number of plants that the same team can manage, allowing for faster and, above all, more controlled growth of portfolios. As a consequence, they allow reducing the operating cost per MW and per MWh.

- To Increase the capacity for detection, quantification and diagnosis of failures and, therefore, to improve the operation of the facilities.

- To generate Key Performance Indicators (KPI) for each element of the installation (modules, trackers, inverters...), which allows delving deeper into the real functioning of the assets. They also allow generating performance indicators for the different actors involved (O&M team, asset management team, financial supervisors…).

Nevertheless, the utilisation of this specific tool does not inherently address the issues highlighted in the preceding section., such as the management of widespread and heterogeneous portfolios or a better control of the O&M teams. In fact, to address some of these challenges, it is necessary to redefine the way in which plants are analysed by creating new indicators (or families of indicators) that provide guidance through the operation process and facilitate the optimization of operation. One of the most obvious and already implemented cases of new indicators has been the incorporation of weather-corrected performance indices: for example, using PR* instead of PR[1]. This way, the operation of plants in different locations and different climate conditions start to be comparable. Some of these new KPIs (as soiling ratios or energetic availability), are almost sector standards, or at least are commonly used, while others (as mean time between failures; acknowledge, intervention and resolution times; fault diagnoses classifications; availability classifications; degradation rates…) are still to be implemented as standards.

The generation of these KPIs improves the analysis capacities of the PMTs, but has the counterpart of considerably increasing the amount of information to be managed. For instance, in a standard 50 MW plant with monitoring at stringbox level, single-row trackers and fifteen-minute data recording, more than 1 million KPIs would be generated per day which is, clearly, unmanageable.

Therefore, to facilitate the operation and optimization of assets, a higher level of integration is necessary, guided by a different logic based on three points:

1. Daily analysis. Unlike fault or alarm notifications, the calculation of KPIs is not urgent. It is therefore possible to operate with them on a daily basis, rather than at the level of individual time steps.

2. Indicators by element type. To improve the overall vision, work must be done with global indicators that integrate the information of all elements of the same type. That is, indicators that shows how the PR representative of all the strings is or how the efficiency of all the inverters is.

3. KPI at different levels. To improve the monitoring of the indicators and the operation with them, new families of indicators must be generated, at different levels, grouping the KPIs of lower levels.

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[1] PR stands for Performance Ratio, the most widespread PV performance evaluation index. PR* stands for a PR corrected to Standard Test Conditions (STC), what implies correcting the effect of temperature and irradiance levels on PV module efficiency.

3. PVOP proposal for management software of PV assets

To create a manageable and useful system of indicators, PVOP proposal focuses first on deciding which process, variables set and analysis path would be the most efficient and comfortable for monitoring a certain problem. For settling a general structure for dealing with those processes, a decision tree logic is proposed (Stiglic, 2012). By definition, a decision tree is a flowchart-like structure in which each internal node represents a "test" on an attribute (e.g. whether an inverter's efficiency is decreasing), each branch represents the outcome of the test, and each leaf node represents the decision taken after computing all attributes (e.g. to clean the air filters).

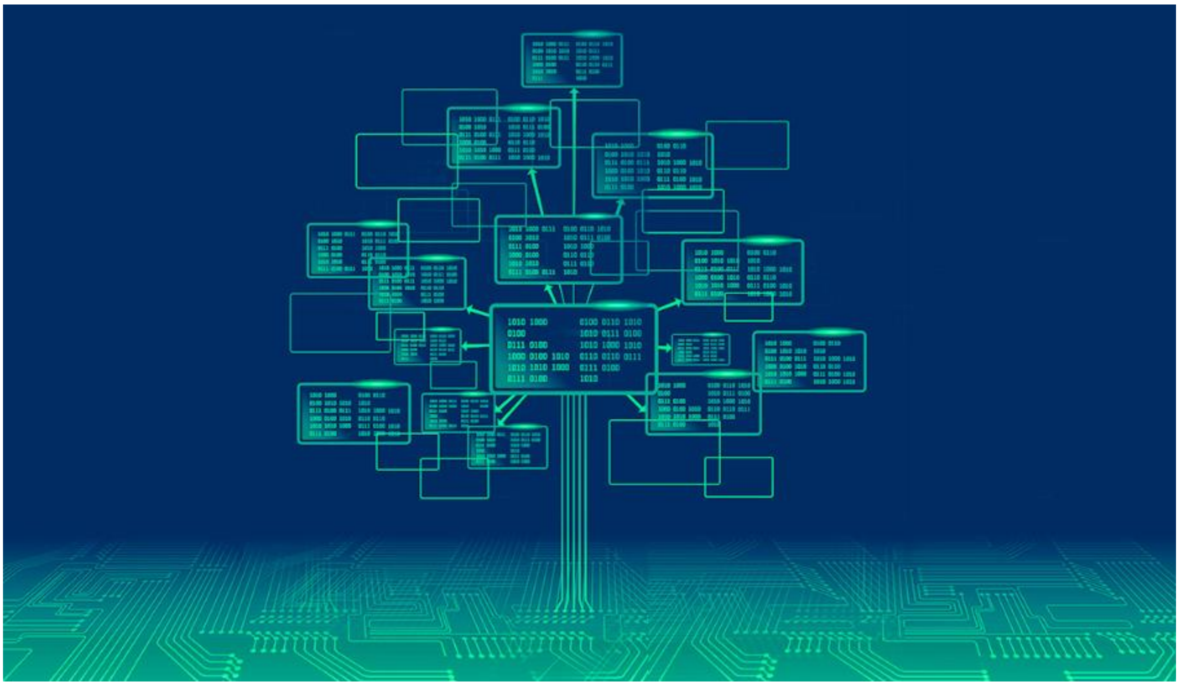

Figure 1. A logic based on a decision tree offers a very natural and accessible path for tracking operation problems.

The objective of the decision tree will be to simulate the exercise of any operator of a PMT who must manage a portfolio and who daily asks him/herself: are all my PV plants performing correctly? If there is something wrong, the decision tree should allow identifying the problem, making the diagnostics, quantifying the related losses and providing the solutions or corrections to make. So, the decision tree should follow a certain order of questions: which PV plant is not working well? Within that plant, what element is failing? Why is it failing? Do all elements of that type fail or only specific ones? In the second case, which of them? How much energy is being lost due to the anomaly? Which level of priority does its resolution has? How can it be solved? How the resolution procedure should be activated and when?

In order to proceed through that decision path, the corresponding families of indicators should be created to allow the PMT operator to solve, at a glance, the test at each node. The analysis should finish with providing a clear diagnostic of the case and an intervention protocol to solve it.

Figure 2 shows an example of the decision tree followed for a problem of operating anomalies in the inverters of a certain installation. Although this process is, perhaps, obvious when working with a small number of elements or assets, it becomes essential when one wants to manage a large portfolio of large plants in an automated and standardized way.

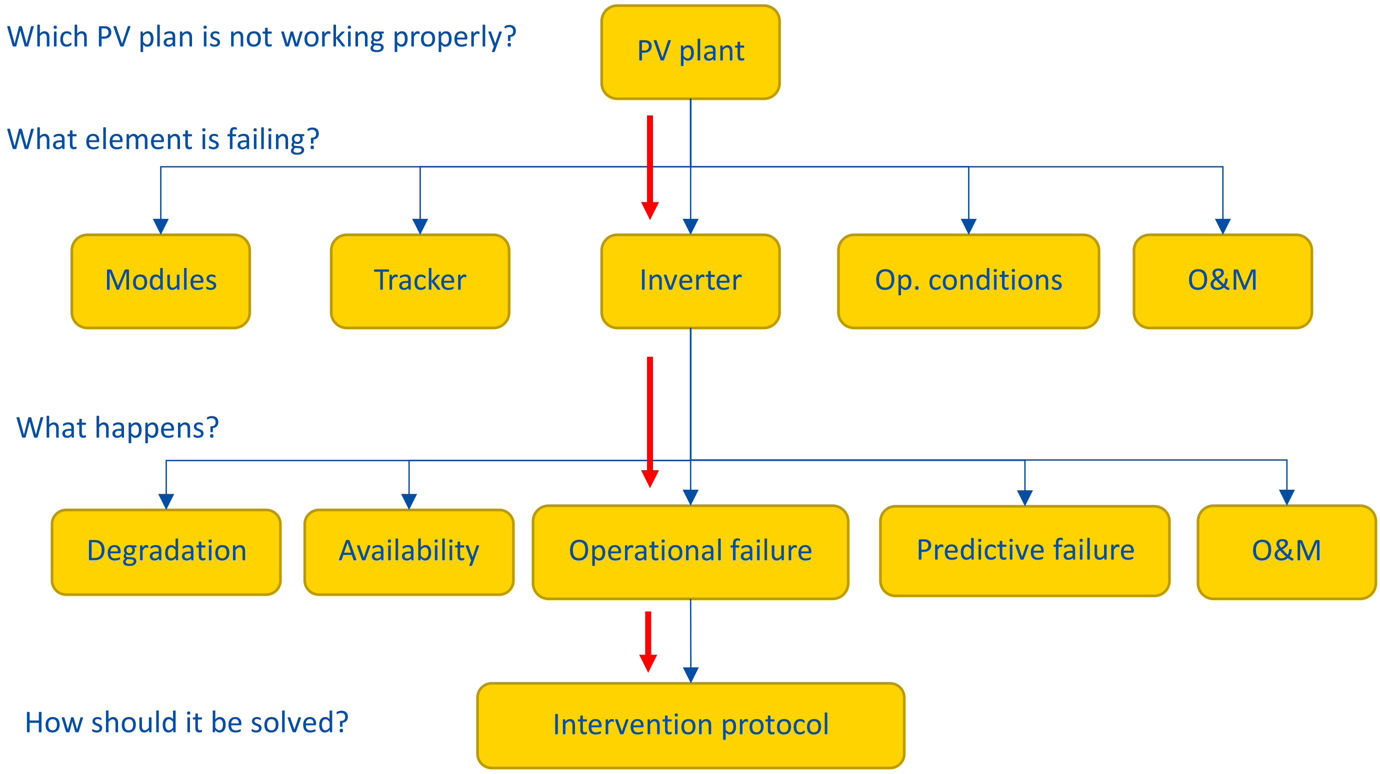

Figure 2. Process for identifying anomalous KPIs following a decision tree

In order to decide the priority of the interventions, the following criteria will be followed, from most to least important/urgent:

- Anomalies that affect the accomplishment of contractual requirements: issues related to the performance and availability indicators that were set in the PV plant's operation contract. This is the first level of performance thresholds that need to be met by a PV plant from the perspective of a PMT operator. Otherwise, contractual claims could be triggered. However, it is worth noting that accomplishing these indicators do not assure an optimized performance. For example, not all the availability losses are usually incorporated in the contractual calculations, so the recovery of these anomalies does not guarantee an optimized performance.

- Anomalies that affect meeting the initial estimates. The second level of thresholds to be met is the comparison of the real performance with the initial estimates, what would assure the fulfilment of the financial model of the

PV plant. In this phase, a first correction of the estimates with the operating conditions must be accomplished. Then, the losses chain must be analysed in order to identify deviation points. This analysis would not finish with the accomplishment of the initial estimated values, but identify any optimization possibility in terms of recoverable energy.

- Predictive interventions. In the context of this Work Package, a predictive issue will be defined as one that does not imply an energy loss (or is currently causing a very low energy loss), but that has the potential to cause significant energy losses in the future, and that can be avoided or limited if it is correctly tackled anticipately. In this category, issues like anomalous temperatures or refrigeration issues in the inverters; air filter or fan changes; early degradation of the components… are included.

- O&M performance. One of the most important aspects to ensure an optimized operation of PV plants is to have a very committed and involved O&M team, capable of decreasing resolution times, giving feedback for the validation of the automatic analysis tools, anticipating anomalies... In the same way that our DET makes it possible to put the experience accumulated over decades at the service of the design of analysis tools to answer the fundamental questions of the operation of PV plants, having an expert O&M team with real in-field knowledge of each specific asset will be the best way to apply, improve and refine these tools and learn from them. This should be encouraged and controlled through the development of specific metrics for the O&M performance in order to obtain the most out of it.

3.1. Multilevel KPIs

The general idea of PVOP's proposal is to work with KPIs at different levels, where high-level indicators will encompass or consolidate the information given by low-level ones. This approach allows a PMT operator to gain a comprehensive yet concise understanding of the status of a PV asset by examining a single, high-level index (just one number), rather than having to engage with numerous indicators. Such unique indicator will be referred to as 'State of Health Index' of the PV plant and will incorporate all the information of the asset performance, therefore giving a much more detailed vision of the state of the installation than a single PR or than the contractual parameters.

On the other extreme, the lowest-level indicators will refer to a specific characteristic of each of the single elements of the PV plant. Main characteristics are:

- Efficiency
- Availability
- Energy loss due to performance failures
- Degradation rate
- Soiling rate
- Non-recoverable losses
- Predictive anomalies

- Communication issues
- Miscalibration
- O&M indicators: intervention, response and resolution times
- Mean time between failures

A nomenclature based on the Greek letter κ will be used to refer to health indices, in which the subscript will indicate both the type and the identifier of the element evaluated and the superscript the characteristic evaluated, as follows:

$$\kappa_{ELEMENT,ID}^{Characteristic}$$

If an indicator does not specify the element identifier, it will be understood to refer to the set of elements of that type existing in the plant, that is, the characteristic value will be all elements of the same type. The value of the indicator for larger periods or for a set of elements of a certain type or location is calculated through weighted averages, being the weighting factors the incident irradiation and the nominal power of each element, respectively.

Then, a consolidation chain will be implemented, where the higher-level KPIs will be calculated from the lower-level ones through:

$$\kappa_i = \sum_n a_{n,i-1} \times \kappa_{n,i-1}$$

Where i stands for the level of the KPI, n represents the number of factors that build up the higher-level KPI and a is the weight given to each of the KPIs. To facilitate the comparisons, all the State of Health indices, κ, will be normalized between 0 and 1. The definition of the components and weighting factors for each of the elements will be part of the core of the work.

However, the following lines give some initial examples of intermediate KPIs:

1. State of health of the PV generator

$$\kappa_{GEN} = a_{GEN1} \times \kappa_{GEN}^{Deg} + a_{GEN2} \times \kappa_{GEN}^{Aval} + a_{GEN3} \times \kappa_{GEN}^{Fail} + a_{GEN4} \times \kappa_{GEN}^{O\&M} + a_{GEN5} \times \kappa_{GEN}^{Data}$$

where each of the components are defined as:

κ_{ST}^{Deg}	Index that evaluates the maximum power that the modules are capable of delivering with respect to their theoretical nominal power. That is, it is an index that will evaluate the degradation of the modules.
κ_{ST}^{Aval}	Index that evaluates whether the element is capable of delivering energy or not. This index will take discrete values, 0 or 1, for each moment.
κ_{ST}^{Fail}	Index that evaluates the presence of anomalies or failures in the operation. It is calculated from the energy availability of the equipment, which includes the

quantification of all the faults diagnosed for it. Failures of elements from other levels are not included.

$\kappa_{ST}^{O\&M}$ Index that evaluates the response of the O&M team to failures of strings or stringboxes. It is calculated from the average failure resolution time. It will take into account the type of failure (to include whether a stock of spare parts is necessary or the ease of resolution of the failure) and will consider expected resolution times.

κ_{ST}^{Data} Index that addresses the quality of the monitoring data for that element. Includes the absence/presence of data and the results of univariate filtering (according to IEC-61724-3) and multivariable (coherence filters).

2. State of health of the PV inverter

$$\kappa_{INV} = a_{IN1} \times \kappa_{IN}^{Eff} + a_{IN2} \times \kappa_{IN}^{Avail} + a_{IN3} \times \kappa_{IN}^{Fail} + a_{IN4} \times \kappa_{IN}^{O\&M} + a_{IN5} \times \kappa_{IN}^{Pred} + a_{IN6} \times \kappa_{IN}^{Data}$$

κ_{IN}^{Eff} Index that evaluates the conversion efficiency of the inverter. It is calculated from the Inverter Weighted Health Index (ISOH), which is a parameter normalized to the expected efficiency of the equipment and would allow the evaluation of performance variations due to factors such as degradation, working temperature...

κ_{IN}^{Aval} Index that evaluates whether the investor is trading or not. It will take discrete values, 0 or 1, for each moment.

κ_{IN}^{Fail} Index that evaluates the presence of anomalies or failures in the operation of the inverter, which are having an impact on its energy production capacity. It is calculated from the energy availability of the equipment which, in turn, is based on the quantification of all the faults diagnosed for it. Failures of elements from other levels are not included.

$\kappa_{IN}^{O\&M}$ Index that evaluates the response of the O&M team to inverter failures. It is calculated from the average resolution time of the failures, it will take into account the type of anomaly and will assume expected resolution times.

κ_{IN}^{Pred} Index that evaluates the presence of anomalies in the operation of the equipment, which do not have a direct impact on its production or which do not represent an energy loss at this time. For example, thermal anomalies in the equipment, current or voltage imbalances, the existence of reverse currents, anomalies with filters or fans...

κ_{IN}^{Data} Index that addresses the quality of the investor's monitoring data. Includes the absence/presence of data and the results of univariate filtering (according to IEC-61724-3) and multivariable (coherence filters).

3. State of health of the sensors of weather and operating conditions

Although they are not part of the energy generation chain, environmental and operating condition sensors directly influence the calculation of contractual parameters and, in addition, have a direct impact on the quality of the analysis that can be done. with the operational data of a plant. Therefore, we have considered an index that reflects its status, which is defined as follows:

$$\kappa_{OC} = a_{OC1} \times \kappa_{OC}^{Cal} + a_{OC2} \times \kappa_{OC}^{Type} + a_{OC3} \times \kappa_{OC}^{O\&M} + a_{OC4} \times \kappa_{OC}^{Data}$$

κ_{OC}^{Cal}	Index that evaluates the state of calibration, installation and maintenance of the equipment. For example, consider whether they are well oriented or clean.
κ_{OC}^{Type}	Index that evaluates the level of monitoring of the plant and the type of sensors it consists of. The existence of more advanced sensors allows for more precise analysis, which will result in a higher index.
$\kappa_{OC}^{O\&M}$	Index that evaluates the response of the O&M team to problems derived from sensors measuring environmental and operating conditions.
κ_{OC}^{Data}	Index that addresses the quality of sensor monitoring data. Includes the absence/presence of data and the results of univariate filtering (according to IEC-61724-3) and multivariable (coherence filters).

4. State of health of the whole PV plant

Once the indicator has been calculated for the main elements of the plant, the indicator for the installation as a whole is calculated as:

$$\kappa_{GL} = a_{GL1} \times \kappa_{GEN} + a_{GL2} \times \kappa_{TR} + a_{GL3} \times \kappa_{IN} + a_{GL4} \times \kappa_{OC} + a_{GL5} \times \kappa_{GL}^{Lim} + a_{GL6} \times \kappa_{GL}^{Des}$$

where the subscript GL means “global” and:

κ_{TR}	Index that evaluates the State of Health of the trackers
κ_{GL}^{Lim}	Index that evaluates non-recoverable energy losses due to grid limitations or restrictions given by the grid operator.
κ_{GL}^{Des}	Index that evaluates energy losses due to design failures

3.2. Intervention protocols

Another key issue for achieving an optimized PV asset management is the establishment of clear and standardized intervention procedures. Once an anomaly has been detected, diagnosed and quantified, the following information flow is activated:

1. Acknowledgement: A notification should be transmitted to both the PMT and the in-field O&M team. Further discussions about the communication priorities will be held, as not all the failures should probably be communicated to all the involved actors: for example, some minor or very straightforward issues should be translated directly to the O&M team while more structural anomalies should need to be managed by the PMT directly with the contractor or with the equipment manufacturers. This procedure will allow minimizing the acknowledgement time.

2. Intervention: Depending on the failure category and impact, an in-field intervention may be necessary. PVOP solution for management software of PV assets will calculate the best intervention option and translate it directly to the O&M team. It is worth noting that not all the assets will have personnel permanently on-site. For sure, not small nor medium-size installations, (e. g. those with power below 3-5 MW), but also in larger PV plants (30-50 MW) the sector is moving to a lesser presence in the field, in order to minimize O&M costs. This means that the intervention itself entails a higher differential cost, so a decision will need to be made in order to establish:

    a. Whether the intervention is individually worth it: for example, a high soiling ratio should automatically activate a cleaning campaign. However, as this entails a significant O&M cost, it should be analysed if cleaning is worth it. In fact, if the notification is received on late September as a consequence of the soiling impact increase during summer months, but the rainy season is to come, it could be maybe better to wait for the natural cleaning than implementing a cleaning campaign.

    b. When the intervention is worth it: for very small failures, the failure resolution can cost more than the benefits coming from the recovered energy. For example, a defective short-circuited diode in a module of a one-axis horizontal tracker installation constructed in a sunny country like Greece could represent an annual energy loss of 400 kWh, leading to an economic loss of 20-80 €. In a worst-case scenario, the cost of waiting a month for resolving the failure will entail an additional loss of 6-7 € with respect to the loss of the month before, which is far lower than the cost of mobilizing a technician to the site in order to resolve the failure. So, the management algorithm will need to have into consideration grouping the failures from different assets in order to minimize intervention costs and taking the highest possible energy out of the resolution.

    c. How the intervention should be accomplished. Definitely at portfolio level, but also at PV plant level, route optimization may be included to minimize the distances run and selecting the better paths between anomaly locations. Additionally, resolution procedures will need to be taken into account in order to select the better implementation. For instance, an intervention in a central inverter entails the disconnection of the medium-voltage cell to isolate the equipment from the AC side and the switch off of all the stringboxes to isolate it from the DC side, what can represent a couple of hours of preparation, apart from the resolution time itself. Usually, these interventions are made during the not-working periods in order to minimize the energetic losses related to the failure. But if the intervention is held at night, it may be incompatible with another intervention that needs to be done during the day, what could change the route selected.

3. Resolution: A resolution protocol should be defined and established as reference a priori for each of the anomalies, and implemented once the resolution phase has been activated. This protocol should include a tool list, safety measures, an intervention procedure and verification measurements. All the information related to the intervention should be gathered and saved for assuring a good traceability and reporting.

The implementation of this intervention management system will lead to a significant reduction in acknowledge, intervention and resolution times and will lead to a better tracking and control of the anomalies that occur in a PV fleet. For example, a technician on-site will perfectly know where to go, with a detailed diagnosis of the issue, will know the tools to be used, how to solve the problem… what will definitely help optimizing times. Additionally, a good reporting will allow increasing the knowledge of the PMT about the failures that occur in their portfolio, controlling better the O&M teams, anticipating to similar issues that could occur in other installations...

4. Development and working plan

The development of the innovations proposed in this work package includes different phases. The next sections present the main milestones in which the work will be divided. A first proposal for each of the phases has been created by the work package partners, after which, an improvement phase will be applied, with the feedback of other stakeholders and external companies interested in PVOP solutions.

4.1. Classification of low-level indicators

The first phase of the work will consist of defining the low-level indices or variables that will later build up the multilevel KPIs system and classifying them in groups aiming to respond to different questions and with different importance. This implies dealing and categorizing different types of indicators that can be classified depending on the responsibilities behind, such as:

- **Contract accomplishment**: indicators that determine whether the plant is fulfilling the contractual requirements. This is the most elementary performance analysis., but its accomplishment is certainly the most important threshold to surpass for a PV plant, so they will need to have an important role in determining the value of high-level indices. Indices of this set are the contractual performance indicator and the contractual availability.

- **Financial model:** a further verification step entails analysing whether the PV installation is complying with the initial yield assessment and its related financial scenario. First, this set of indicators includes the comparison between the real and the estimated productions at different levels (PV plant, inverter, DC entries or strings). Furthermore, the comparison in terms of losses can be very useful to identify the point of the losses chain in which the deviation occurs (irradiance gain, temperature, DC/AC conversion, wiring, limitations…).

- **Equipment performance anomalies**: energy losses due to performance failures at PV generator, tracker, inverter or PV plant level; degradation and ageing; predictive failures; data availability…

- **O&M performance**: indicators related to the O&M detection, intervention or resolution times, losses due to soiling or vegetation and their related cleaning and cutting campaigns, equipment replacement, stock of spare parts.

- **Grid integration**: indicators related to market prices, battery cycles, curtailments and constrictions.

4.2. Definition of the decision tree

Once all the low-level parameters have been identified and classified, the decision tree should be constructed. This implies deciding how to group the lower-level KPIs into the upper-level ones in order to have full visibility of the possible problems that could affect a PV installation. In this stage, achieving full coherence of the KPI structure will be mandatory, of installations of different sizes, tracking strategies, climatic conditions…

The second step is to determine the weighting factors, which are necessary to ensure comprehensive visibility of potential anomalies and to assign appropriate importance to each KPI family.. Once constructed, the warning thresholds will have to be fixed for each of the casuistry. For both the weighting factor and the warning threshold selection, basic AI techniques will be considered, such as clustering. However, while the warnings could be activated dynamically and depending on different conditions, the weighting factors will need to remain fixed once and for all, so that different periods and PV plants can be coherently compared.

4.3. Integration of different data sources

One of the advantages of generating a general structure as proposed in this work package is that it is independent of the specific KPIs. Therefore, it allows to easily integrate any improvement in the low-level KPIs. For example, any development in the failure detection capabilities thanks to the application of new AI algorithms, or predictive analyses, or info coming from aerial images (IR, EL, PL…) will each of them impact on a defined KPI and improve the management capabilities at PV portfolio level.

4.4. Working plan

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Definition of the working plan												
Classification of low-level indicators												
Definition of the decision tree												
Lab testing: functional validation												
Integration of different data sources												
Field testing												
Adjustment after validation												

Table 1. Gantt diagram of the main work package developments

5. Solution testing and KPIs

The implementation of PVOP solution for management software of PV assets will need to be validated to guarantee the correct performance of the algorithms and to quantify its benefits. For this purpose, we will define a set of tests in a real environment and a set of KPIs to evaluate its performance.

5.1. Solution testing

The main particularity of the validation phase of this Work Package in relation to others is that it cannot be validated in a controlled environment (that is, in laboratory) nor in the facilities of the consortium. Failure types need to be real and representative of the issues that the industry is currently facing. So, the algorithms need to be tested in a portfolio or fleet of PV plants, as large, widespread, heterogeneous and representative (in terms of technology, climate, design, grid limitations…) as possible.

However, as a first validation step in the first period of the project, an alternative here is to test the algorithms with past operational data from the PV fleet managed by the Consortium and to estimate the performance gain if the solution had been applied. The advantage of this approach is that, from the very first moment, we will be facing real problems, not only in its nature (see section below) but also in its occurrence and impact. This will be very useful in order to test the results, tune the weighting factors and validate if all the anomalies are 'visible' through the different levels of KPIs.

For this, we will establish two testing procedures, on the one hand, we will take advantage of the PV plants supervised by the PVOP's consortium members and, on the other, of the PV fleet of some stakeholders of the European Industry (SEI): some of the DET members and some other external companies interested in PVOP solutions who will be selected and invited to collaborate to the project during its progress.

5.1.1. Tests in the PVOP's consortium portfolio

One of the PVOP's consortium members commercial solutions is PVET®, a cloud-based digital service for the continuous analysis of PV plants' operation. This service is based on a Big Data system that combines AI and parametric algorithms and which allows optimizing the long-term production and O&M costs of the PV plant. This service is currently analysing data in real time in about 6 GW of plants around the world with between 1 and 10 years of operational data (see Figure 3). It includes PV plants with monofacial and bifacial modules; installations in climates as different as dry/desertic (Atacama, Kalahari, Sonora, Sahara), mediterranean (Spain, Italy, Portugal) or tropical (Brazil, Dominican Republic); static and 1-axis horizontal (multirow, bi-row and mono-row) and azimuthal tracking systems; central and string inverters.

As a first validation step, PVOP will implement this solution in our own portfolio to test the KPI structure and composition, define the weighting factors and the intervention protocols; and also debug errors and validate the overall performance of the solution.

A first impact estimation, the PVOP's consortium PV portfolio has already been characterized in energy losses terms. Performance anomalies are classified in two categories: recurrent failures and critical episodes. The first ones are those operational failures that usually occur in a PV plant, and which are not very energy intensive: inverter or tracker stops, open strings, tracking misalignments, short-circuited diodes, temperature anomalies… Those failures account for 0,9% of annual energy losses. On the other hand, critical episodes are those that occur occasionally but which have a very significant energy impact. Most of the times, these types of failures are related to serial defects, design defects or widespread degradation: cooling fan breakage, tracker batteries discharge, non-optimized back-tracking algorithm, inverter burnouts… These failures typically occur only 2-3 times in the PV plant's lifetime but account for very large energy losses: 4-6% in the year they occur and an additional overall 0.6% energy losses.

Figure 3. Geographical distribution of the PV plants of the PVOP's consortium portfolio.

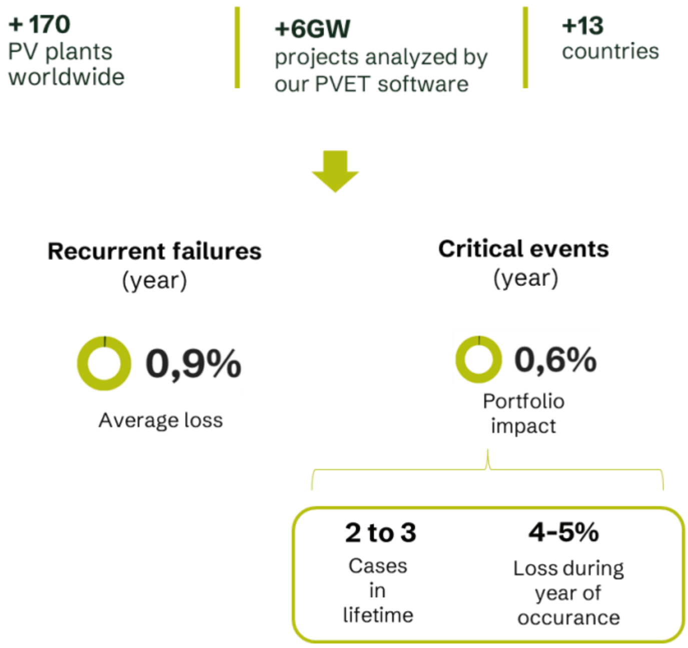

Figure 4. Main characteristics and energy losses of the PVOP's consortium portfolio

We will test the algorithms with past operational data from the PV fleet managed by the Consortium and to estimate the performance gain if the solution had been applied. In order to reach this stage, the solution must be complete, tested and validated to TRL 6.

5.1.2. Tests in the portfolios of external stakeholders

During the first year of the project, the PVOP consortium will identify possible external Stakeholders of the European Industry (SEI) in whose portfolios apply our solution. The objective of this second validation phase during the second period of the project will be to drive the solution to TRL 7. As a first option, the members of the DET will be contacted and asked to become SEI. Then, further external companies will be identified and contacted through the WP6 activities based on Open Science techniques. A Non-Disclosure Agreement will be signed between the parties and, if requested, a collaboration agreement will be also signed.

In order to guarantee the correct validation of PVOP's solution as well as the interests of all the parties, the key aspects of this collaboration will be the following:

- The SEI will let PVOP to access the operational data of its PV portfolio. This could be done through an API service or through a reading access to a database. Main variables needed will be: electrical variables (current, voltage and power) at PV plant, inverter, stringbox and string (if available) levels; meteorological variables (GHI, GTI, Ta, Tc…); position variables from the trackers; and alarms and operation signals (from inverter, trackers and the PPC). Additionally, the SEI will need to provide the data from the O&M activities, to calculate KPIs and validate the solution. This data will include reports and feedback from in-field verifications, what will allow to further improve the algorithms and weighting factors distribution.

- PVOP will analyse the historical data of the client and calculate the main KPIs related to its performance: energy loss, mean time between failures, acknowledgment, intervention and resolution times.

- Then PVOP will implement its advanced management solution to the PV portfolio. After a representative operation period (minimum of 3 months), the main KPIs related to the PV portfolio performance will be recalculated and the improvement will be assessed. For this final phase, the SEI will need to provide some time dedications and operational costs to the PVOP team, in order to correctly quantify the impact of the innovations.

5.2. KPIs

This section details the KPIs proposed to evaluate different aspects of the solution implemented. The evaluation KPIs will be structured in two levels: technical KPIs and general KPIs

5.2.1. Technical KPIs

The objective of the technical KPIs is to validate the structure of the solution (see Table 2) and its performance (see Table 3). The multilevel KPI structure will be designed to assure a panoramic view of the whole asset portfolio. So, the consolidation and summary of the hundreds of KPIs that are produced by each of the PV assets into a few high-level indicators will be assumed by definition. However, it is also mandatory that this multilevel structure is capable of providing visibility of the main problems that could arise in the PV portfolio operation. So, the first thing to validate is this visibility for all the main types of failures. First, anomalies and incidences will be classified into major and minor, depending on the economic and energetic impact of their consequences. Then, a technical KPI will consider if the high-level indicators allow detecting the appearance of each of the failures included in the lower-level indicators, depending on the weighting factors and the KPIs structure itself. Then, standard performance KPIs will be calculated in order to validate the system outcomes (true/false positives and false negatives). For this validation, the collaboration of the O&M teams will be crucial.

KPI	Expected output/value
Severe issue visibility	1/0
Low-level issue visibility	1/0
True positives	>95%
False positives	<5%
False negatives	<5%

Table 2. Main technical KPIs proposed for the validation of the system structure

Once the system will be into operation, its impact will be measured by comparing the performance of the PV portfolio before and after its implementation. Although this quantification exercise entails a considerable uncertainty (for example, it will depend on whether a critical event has occurred before and after the implementation of the new system), representative numbers are expected at portfolio level. For this purpose, some precautions will need to be taken:

- It will be crucial to have a good analysis capability of the ex-ante situation to accurately define the starting point.
- No changes will be made in the index's composition nor in the weighting factors through the whole process.
- Accurate feedback from the O&M teams will be enabling for further calculations.
- Anomalies classification will allow respecting the responsibility chain and correctly allocating the unavailability. For this, IEC TS 63019:2019 will be followed.

KPI	Expected output/value
Detection time	**80% reduction**
Performance drop	**<= 1 week**
Major op failures	**<= 15 min**
Minor op failures	**<= 2hours**
Availability	**<= 15 min**
Sensorisation	**< 1 day**
Predictive failures	**< 2 days**

Time resolution	**30% reduction**
MTBF	**25% increase**
Critical events	**50% reduction**
Energy losses	**75% reduction**

Table 3. Main technical KPIs proposed for the validation of the system performance

It is worth noting that the real improvement in some of the above-mentioned indicators depend not only on PVOP's developments but also on external factors such as, for example, the response time of the O&M team or the availability of spare parts. These external factors are, unfortunately, out of the control of the consortium and can limit the capabilities of our solutions. However, PVOP's tools will be also oriented to monitor, measure and optimize these external factors in order to allow closing the gap with the theoretical potential of the solutions.

5.2.2. General KPIs

Finally, a link between the previous technical KPIs and the general KPIs of the project will be constructed in order to measure and quantify the real impact of the innovations of this Work Package (see Table 3).

KPI	Expected outcome
PR*	**1.5% increase**
Availability	**1.5 % increase**
Energy losses	**75% reduction**
Performance increase	**3.0% increase**
Increase in annual profitability	**€4 M/GWp**
O&M and PV asset management cost	**32% reduction**
False alarms	**90% reduction**
Back-office analysis time	**80% reduction**
PMT costs	**25% reduction**

Table 4. Main technical KPIs proposed for the validation of the system performance

6. Conclusions

This document presents the concept proposal for the developments of WP5 of the PVOP project. It describes the problems that are currently faced by PV plant owners and operators when trying to optimize the performance of their PV portfolio and the need for establishing standard procedures, calculation methodologies, comparison metrics and summarizing indicators in an environment with larger and widespread assets working on different climate regions and grid ecosystems, which produce massive amount of operational data, stressed by reduced OPEX budgets and needed to be controlled be limited PMTs.

Then it defines the main technical solutions proposed by the PVOP project to tackle this challenge and to achieve durable, optimized, predictable long-term performance. In a few words, a multilevel KPIs structure is proposed, where high-level indicators will encompass or consolidate the information given by low-level ones, allowing PMT operators to have a very simple and quick overview of the state of a PV asset by looking only to few high-level indices instead of dealing with hundreds of indicators but, on the other hand, to have a much deeper insight and detailed vision of the installations than the one provided by current state-of-art KPIs. Besides new performance metrics, intervention protocols or optimized O&M routes will be also provided.

Then, validation procedures and their associated evaluation metrics are also presented. First, we will take advantage of the PV plants supervised by the PVOP's consortium members and, on the other, of the PV fleet of some Stakeholders of the European Industry (SEI): some of the DET members and some other external companies who will be selected and invited to collaborate with the project during its progress. Then, technical KPIs are pre-defined for the system performance evaluation together with their link to the general project KPIs.

7. References

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