Artificial Intelligence for Operation and Maintenance of PV Plants

Deliverable D4.2

Demonstration Plan

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EXECUTIVE SUMMARY

This deliverable lays down the baseline for the validation of the AI4PV solutions, under the umbrella of **T4.2 Validation in PV farm**.

As a result, a clear view of the complete methodology for the definition of the demonstration plan is presented, as well as an overview of the demonstration site and the architecture in place for data collection and processing.

This document reports the functional requirements for each UC addressed within the project and the list of KPIs to be monitored during the demonstration necessary to validate the AI4PV solutions via a CBA carried out in T4.3.

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ABBREVIATIONS AND ACRONYMS

Acronym	Meaning
AI	Artificial Intelligence
API	Application Programming Interface
CBA	Cost-Benefit-Analysis
DT	Digital Twin
HTTPS	Hyper Text Transfer Protocol Secure
ML	Machine Learning
O&M	Operation and Maintenance
SoTA	State of The Art
UC	Use Case
VPN	Virtual Private Network

GLOSSARY OF KEY TERMS

Artificial Intelligence	Artificial intelligence is a wide-ranging branch of computer science concerned with building smart machines capable of performing tasks that typically require human intelligence.
Machine Learning	Machine learning is a method of data analysis that automates analytical model building. It is a branch of artificial intelligence based on the idea that systems can learn from data, identify patterns and make decisions with minimal human intervention.
Deep Learning	Deep learning is a subset of machine learning, which is essentially a neural network with three or more layers. These neural networks attempt to simulate the behaviours of the human brain—albeit far from matching its ability—allowing it to "learn" from large amounts of data.
Fault	A fault is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual standard condition.
Failure	Permanent interruption of a system's ability to perform a required function under specified operating conditions.
Malfunction	Intermittent irregularity in fulfilment of a systems desired function.
Fault detection	Determination of faults present in a system and time of detection.
Fault diagnosis	Determination of kind, size, location and time of detection of a fault by evaluating symptoms. Follows fault detection. Includes fault detection, isolation and identification

1. INTRODUCTION

This document, deliverable **D4.2 Demonstration Plan**, details the implementation plan to be followed in order to integrate and test the AI4PV solutions in the identified demonstrator.

1.1 SCOPE OF REPORT

This deliverable focuses on the final stage of the project, since it aims at defining the framework for the validation of the system. The validation of the project solutions starts with data acquisition, storage and it culminates with the execution of algorithms and scripts for the detection of anomalies in the behaviour of PV operational data.

This document includes a summary of the methodology used to define the implementation and demonstration plan and which was adopted during the project. It also includes the technical requirements of the addressed UCs as well as their compliance with the demonstration set-up.

The results here presented have been achieved in the development of task **T4.2Validation in PV farm**, included in the context of the work package **WP4 Validation** and will be key for the validation and demonstration of the AI4PV solutions. The result achieved during the demonstration will be fundamental for the CBA of T4.3 that will benchmark the performance of the AI4PV tools against SoTA solutions.

1.2 OUTLINE OF REPORT

This report is structures as follows:

- ***Chapter 1*** introduces the scope of the document
- ***Chapter 2*** focuses on the methodology adopted to streamline the demonstration plan
- ***Chapter 3*** digs into the specific demonstration with an overview of the AI4PV architecture needed for data collection and processing.
- ***Chapter 4*** provides the specific implementation plan for each UC including the functional requirements that must be met in order to ensure compatibility and operability of the AI4PV solutions.

2. METHODOLOGY

Although ordinary methodology of implementation and demonstration plan intends establishing actions' order to achieve the conditions for demonstration, in AI4PV, it intends also, in one hand, to guarantee that results are measurable and comparable, enabling an accurate CBA in T4.3 and, on the other hand, to allow for the different demos to come together and exchange experiences [REF GA].

In this sense, general objectives of the implementation plan are the following:

- Have a detailed plan for each demonstrator, including:
    1. Installation and configuration of equipment and/or systems;
    2. Detailed plan for the measurement and calculation of the KPIs;
- Promote discussion among demonstration leaders and technology providers;
- Have results measurable and comparable for accurate CBA in T4.3.

Having the objectives identified, the proposed methodology main steps will address each one of them. The followed methodology is summarized in Table 2-1.

TABLE 2-1: METHODOLOGY STEPS ADDRESSING IMPLEMENTATION OBJECTIVES

Objectives / Steps	Detailed plan for each demonstrator		Promote discussion among demonstration leaders and technology providers	Have results measurable and comparable for accurate CBA in T4.3
	Installation & configuration of equipment	Plan to measure/ calculate KPI		
Literature review	●	●		
Define UC and KPIs based on user needs	●	●	●	
Refine UC and technical requirements based on demonstration field conditions		●	●	●
Identify additional sensors and equipment to be installed in order to address the targeted UCs	●		●	

Ask use case demonstrators to decide which KPI should be kept or discarded		●	●	●
Formulate KPIs for different UCs		●	●	●
Risk assessment	●		●	
Field preparation	●		●	
Field demonstration		●	●	●

When putting the methodology on the field, the mentioned steps had to receive the contributions from other tasks, so Task 4.2 has built a framework for implementation and demonstration, which is depicted in Figure xx. Each displayed task follows the description stated in [REF GA].

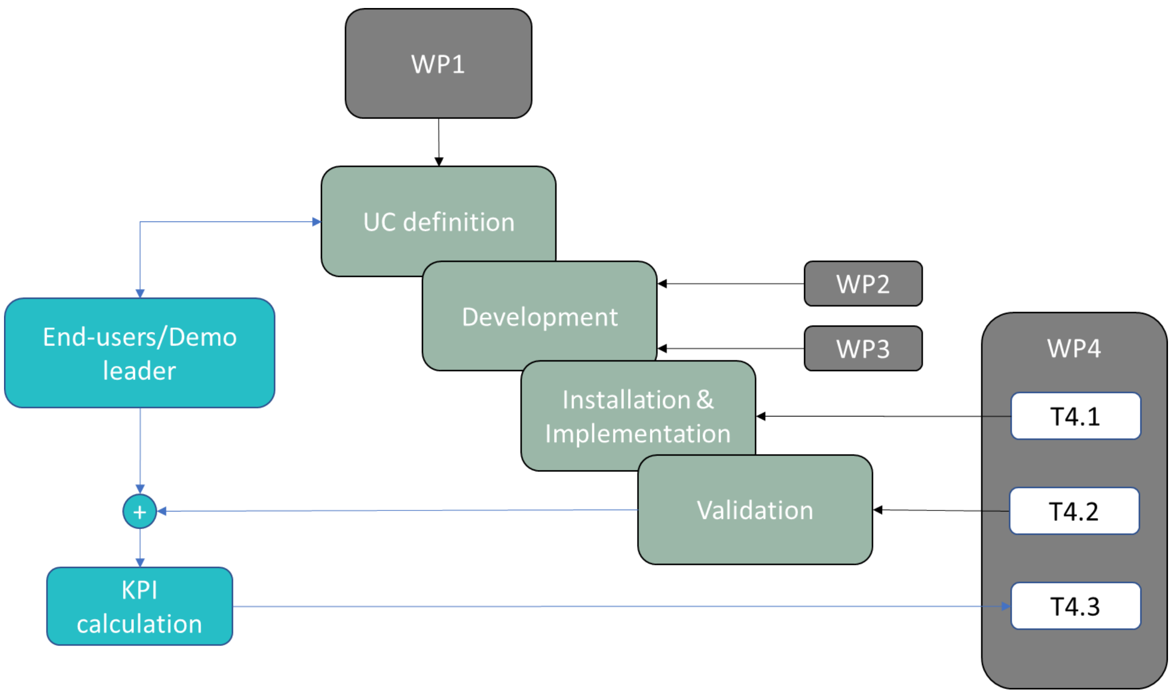

FIGURE 2-1: AI4PV'S IMPLEMENTATION FRAMEWORK

3. DEMONSTRATOR

3.1 MONTE DAS FLORES PV FARM – PORTUGAL

Monte das Flores solar park is located in Évora district at 130km from Lisbon. It's a 2,9MWp solar park composed of 9.360 monofacial solar panels arranged in 156 strings feeding two central inverters. Each string follows a 3P20 configuration with a 20º tilt angle fixed structure. Real time monitorization provides information from the transformers, central inverters and combiner boxes. Soiling measurement is also available, and thermography imaging will also be available in an annual basis.

The characteristics of this solar parc (size, location, time under operation) provides an excellent framework to develop and test new technologies and strategies for O&M, and further scale them up to cope the current trend of increasing the size and capacities of solar parks.

FIGURE 3-1: MONTE DAS FLORES PV PARK

Figure 3-2 shows a detail of the data acquisition process proposed for the project AI4PV, which will allow the implementation of the complete AI4PV platform and its automatic operation. As it can be appreciated, using a VPN for safe and secure interaction, data extraction will take place, in order for a preliminary normalization and transformation before the final load is done. Data will then be available for its use, and both the original data and the results will be accessible for developers and for operators and end users, which, using an API endpoint via HTTPS, will be able to validate the performance and results of the developments.

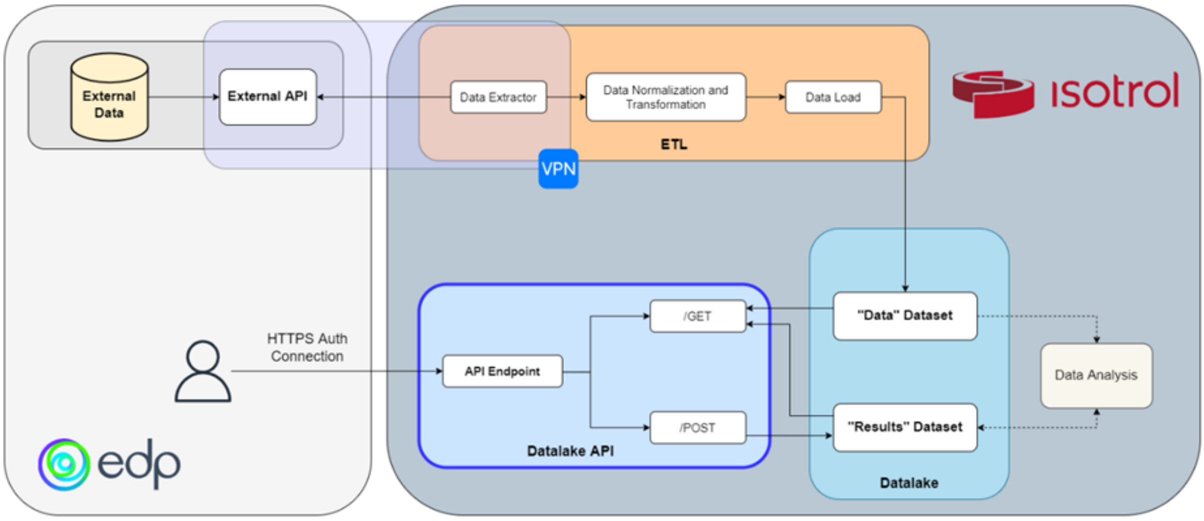

FIGURE 3-2: DATA ACQUISITION AND STORAGE PROCEDURE

The first storage will consist of a series of tables that include all the data that has been extracted, accessible by different authorized users. This will allow that different algorithms, models and systems are executed in different environments and virtual machines. The results that each analysis generate will later be stored in a different table in a structured manner, allowing the post-processing of the results obtained regarding the detection and prediction of failures, generating recommendations according to economic considerations related to O&M.

The extraction process will be configured in a way that ensures that all the signals are retrieved in a structured and usable manner. The data extraction and the initial transformation and load process will ensure, first of all, that all the necessary signals are retrieved and, secondly, that the data which is finally uploaded to the datalake follows the required timeframes. Data will be structured ensuring that timestamps are aggregated with a granularity of **5 minutes**.

As for the specific data retrieving and upload frequency, there are several considerations to keep in mind. Normal operation and daily reports generation will need a daily extraction of data, however, in order to empower digital twin results, lower frequencies, closer to the range of several minutes, will be considered. Depending on the final identified needs of operational systems, and the technical viability of the data extraction, a final frequency will be defined.

4. UC SPECIFIC IMPLEMENTATION AND DEMONSTRATION PLAN

This section covers the implementation plan of AI4PV's UCs, considering either leader or learner roles. For each UC, the presented information follows the same flow:

1) **brief general introduction** addressing its scope, objectives and a summary of the interactions between suppliers and demonstrators, referring the solutions provided;

2) **demonstration requirements** identified by the developers and, in some cases, demonstrators;

3) **chronogram for implementation** of the solutions listed in the previous subsection (and, in some cases, the following subsection), with the expected dates and associated implementation sites rendered for the four implementation stages – Supply/Receiving, Validation, Installation/Configuration and Commissioning;

4) **functional requirements** of some of the solutions presented in the previous subsections, as well as for other stand-alone equipment.

Table 4-1 sums up the information related to each UC, specifically the solutions to be implemented, as well as the responsible to supply that solution. As explained in D4.1 "Validation framework definition" EDP NEW and ISOTROL are the main responsible for the integration: EDP NEW is responsible for collecting, via a VPN, operational data from the demonstrator, while ISOTROL is responsible to integrate and implement the data flow between the different solutions via an API.

TABLE 4-1: AI4PV TO-BO-IMPLEMENTED SOLUTIONS

UC	Solution	Developer
UC1 – Descriptive analytics	*PV panels: Soiling rate*	ISOTROL
	Inverter malfunctions detection (shutdown, temperature disconnection, Out of normality analysis)	ISOTROL
	Solar field problems detection (sensor malfunction, tracker blocking, panel ageing, etc)	ISOTROL
	PV panels: Soiling rate	EDP NEW

UC2 - Prescriptive analytics tool: root cause analysis	*<u>Inverter malfunction detection</u>* (power electronics' malfunction, inverter shutdown)	INESC TEC
	<u>Power transformer malfunction detection:</u> out of normality analysis, underperformance, Open circuit and short circuit	EDP NEW
UC3 - Cost-optimised predictive maintenance approach	*<u>Optimal O&M scheduling for RoI optimisation</u>*	EDP
	<u>Asset replacement – Action prioritisation</u>	INESC TEC

To each functional requirement listed throughout this chapter is assigned a colour, identifying the qualitative degree of fulfilment ensured by the demonstrator leader to the suppliers (or vice versa), with the following meaning:

- total compliance:
- partial compliance:
- no compliance:

This qualitative attribution of a compliance level is applied henceforth.

4.1 UC1 – DESCRIPTIVE ANALYTICS

The present UC entails the use of DT tools for early fault and failure detection and diagnosis of PV plants as extensively described in D1.1 "Use cases for O&M of solar power plants" [1]. Based on electrical data and meteorological data, a DT system will help the supervisor of the plant to detect the most common problems that may happen in solar parks representative of the UCs addressed within the project.

4.1.1 DEMONSTRATION REQUIREMENTS

Table 4-2 presents the conditions required by the developer (ISOTROL) in order to successfully implement and demonstrate the respective solutions. The compliance level of the demonstrator is also reported.

TABLE 4-2: UC1 FUNCTIONAL REQUIREMENTS

AI4PV solution	Functional requirements		Compliance level
PV panels: Soiling rate	Information about the PV plant layout	Access to information about PV plant configurations (i.e. tilt angle, azimuth angle, number of strings, etc)	(green) This information have been shared by the demonstrator leader, including drawings and blue prints of the PV plant, as well as datasheets
		Information about the location of the sensors and meteorological station inside the PV plant	
	Historical data to calibrate the model[1]	Historical meteorological data of the demonstrator to calibrate the DT models for soiling detection	(green) Historical operational data of the demonstrator have been shared from 2018 until 2021, including measurements of the meteorological sensors
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	(yellow) The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this

[1] The list of data is extensively described in [2]

			approach won't allow the collection of real-time data but rather of the previous 24 hours
Inverter malfunctions detection	Information about the PV plant layout	Access to information about Inverter configurations and technical characteristics	Line diagram showing the plant configuration and datasheets of the inverters were shared
	Historical data to calibrate the model	Historical data of inverters installed in the demonstrator to calibrate the DT	Historical operational data of the demonstrator have been shared from 2018 until 2021, including measurements related to power electronics
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours
Solar field problems detection	Historical data to calibrate the model	Historical operational data of the demonstrator to calibrate the DT	Historical operational data of the demonstrator have

			been shared from 2018 until 2021,
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours

4.2 UC2 – PRESCRIPTIVE ANALYTICS TOOL: ROOT CAUSE ANALYSIS

The present UC entails the use of AI and ML tools for early fault and failure detection and diagnosis of PV plants as extensively described in D1.1 "Use cases for O&M of solar power plants" [1]. Based on electrical data and meteorological data, this AI layer will help the supervisor of the plant to detect the most common problems that may happen in solar parks representative of the UCs addressed within the project.

4.2.1 DEMONSTRATION REQUIREMENTS

Table 4-3 presents the conditions required by the developers (INESC TEC and EDP NEW) in order to successfully implement and demonstrate the respective solutions. The compliance level of the demonstrator is also reported.

TABLE 4-3: UC2 FUNCTIONAL REQUIREMENTS

AI4PV solution	Functional requirements		Compliance level
PV panels: Soiling rate	Information about the PV plant layout	Access to information about PV plant configurations (i.e. tilt angle, azimuth angle, number of strings, etc)	This information have been shared by the demonstrator leader, including drawings and blue prints of the PV

		Information about the location of the sensors and meteorological station inside the PV plant	plant, as well as datasheets
	Historical data to train the model[2]	Historical meteorological data of the demonstrator to train AI models for soiling detection	Historical operational data of the demonstrator have been shared from 2018 until 2021, including measurements of the meteorological sensors. This were complemented by historical data collected from Copernicus ERA5 [2] in order to have a more reliable analysis
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours
Inverter malfunctions detection	Information about the PV plant layout	Access to information about Inverter	Line diagram showing the plant configuration

[2] The list of data is extensively described in [2]

		configurations and technical characteristics	and datasheets of the inverters were shared
	Historical data to train the model	Historical data of inverters installed in the demonstrator train the AI models	Historical operational data of the demonstrator have been shared from 2018 until 2021, including measurements related to power electronics
	Historical data of faults and failures of the inverters	Historical data of faults and failures of the inverters are key to train AI models for the detection of abnormality conditions.	Since the beginning of the operation of the demonstration faults and failure of the power electronics weren't registered. To cope with this unavailability of data, synthetic dataset were employed to train the models.
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours

Power transformers malfunctions	Historical data to train the model	Historical data of transformers installed in the demonstrator to train the AI models	Historical operational data of the demonstrator have been shared from 2018 until 2021, including measurements related to power transformers
	Historical data of faults and failures of the power transformers	Historical data of faults and failures of the power transformers are key to train AI models for the detection of abnormality conditions.	Since the beginning of the operation of the demonstration faults and failure of the power transformers weren't registered. To cope with this unavailability of data, synthetic dataset were employed to train the models.
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours

4.3 UC3 – COST-OPTIMISED PREDICTIVE MAINTENANCE APPROACH

The present UC aims at validating AI4PV's task-recommendation engine as supportive tool for O&M operators of PV plants. Based on historical data analytics by AI, ML algorithms combined with a DT tool will help the supervisor of the plant with causes and solutions of the most common problems of a PV plant. Besides the AI, ML, and DT tools, the usage of previous maintenance reports will play a key role in the development of the recommendation system.

4.3.1 DEMONSTRATION REQUIREMENTS

Table 4-4 presents the conditions required by the developers (INESC TEC and EDP NEW) in order to successfully implement and demonstrate the respective solutions. The compliance level of the demonstrator is also reported.

TABLE 4-4: UC2 FUNCTIONAL REQUIREMENTS

AI4PV solution	Functional requirements		Compliance level
Optimal O&M scheduling for RoI optimisation	Reports of O&M campaigns in the demonstrator	Access to information about PV plant historical faults and failures as well as interventions	(green) This information have been shared by the demonstrator leader, including reports of previous interventions
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	(yellow) The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours
Asset replacement – Action prioritisation	Reports of historical failures in the PV park	Access to information about PV plant historical faults and failures as	(green) This information have been shared by the demonstrator

		well as interventions and costs	leader, including reports of previous interventions
	Access to real-time data for test and final validation	Integration between AI4PV solutions and demonstrator, to collect and process operational data via the developed solutions	The information from the SCADA will be collected via VPN and transferred through an API to the AI4PV solutions. Nevertheless this approach won't allow the collection of real-time data but rather of the previous 24 hours

5. LIST OF KPIS

Table 5-1 shows the list of KPIs to be measured during the demonstration in order to validate the developed solutions.

TABLE 5-1: LIST OF KPIS TO BE MONITORED AND MEASURED DURING THE DEMONSTRATION

#	Name	Description	Formula	Target	UC
KPI1	Root mean squared error (RMSE) between empirical and reproduced I-V curve	It represents the difference between the empirical I-V curve provided in the datasheet of the PV module and the reproduced curve through the DT modelling	$RMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(I - I_i)^2}}{Isc}$ Where: • $I_i, \hat{I}_i$ are the real and modelled output current of the PV module. • N is the number of samples of the empirical I-V curve • Isc it's the short circuit current of the PV module	<0.6	1
KPI2	Reduced soiling losses (RSL)	It represents the ratio between the energy of the soiled PV panel and the cleaned one. The higher it is, the more cleaned the PV is for a long period of time. It considers losses due to both dust or organic soiling	$RSL = \frac{\int_0^T P_{PV\_soiled}\,dt}{\int_0^T P_{PV\_cleaned}\,dt}$ Where: • $P_{PV\_soiled}, P_{PV\_cleaned}$ are the output power of the soiled and cleaned PV; • T is the observation time, it can be 1 week, 1 month, etc	>80%	1-2
KPI3	Number faults and/or failures detected automatically	The inspection of the SCADA and sensor data of the inverter by AI, ML	$NF = \frac{Number\_faults\_detected\_AI4PV}{Number\_faults\_registered\_O\&M\_team}\%$	80%	2

	through data analysis	algorithms will detect trending and deviations in the measurements that may indicate a fault or a failure in the PV plant			
KPI4	Fault Detection accuracy	It's the ratio between true faults detected by AI4PV and real faults	$FDA = \frac{N\_true\_positive\_fault}{N\_true\_positive\_fault + N\_false\_positive\_fault} \%$	>80%	2
KPI5	Number of maintenance actions at validation site	Depending on the output of the recommendation system, predictive maintenance may be carried out to avoid failures. It is the number of interventions advised to the O&M team by AI4PV recommender system.	n.a.	>=2	3
KPI6	Recommendation accuracy (RA)	Number of correct recommendations	$RA = \frac{N\_good\_recommendation}{N\_tot\_recommendation} \%$	>70%	3

KPI7	Percentage of losses & degradation underperformance quantification (AEL_UD)	The early detection of faults in the PV plant is important to avoid power losses that, otherwise, would be undetected until a failure occurs	$AEL\_UD = \frac{\int Psaved\ dt}{\int Ptot\ dt} \%$	< 5%	2
KPI8	Avoided energy losses due to early detection problems (AEL_ED)	Avoided energy losses due to fault detection at early stage	$AEL\_ED = \frac{\int Psaved\ dt}{\int Ptot\ dt} \%$	4%	1-2
KPI9	Reduce unexpected outages (RUO) in the transformer stations	It's the ratio between the outages registered with the AI4PV solutions in place, and the ones registered without AI4PV. The outages are avoided through early detection of failures that would allow to intervene before	$RUO = \frac{Out\_AI4PV}{Out\_noAI4PV}$ Where: • Out_AI4PV, are the outages registered with AI4PV solutions in place • $Out\_noAI4PV$ are the outages registered without AI4PV solutions in place	<96%	2

		the worsening of the failure.			
KPI10	Reduce response time	It is the time between failure occurrence and detection	$$RRT = \frac{RT_{AI4PV}}{RT_{conventional}}\%$$ Where: • RT_{AI4PV} is the response time with AI4PV in place, for a particular failure; • $RT_{conventional}$ is the conventional response time (without AI4PV) for a particular failure.	<90%	1-2
KPI11	Plant availability increase (PAI)	It is the number of working hours ensured by AI4PV by reducing the number of downtimes.	$$PAI = \frac{N_{hours\_availability\_wAI4PV} - N_{hours_{availability_w}/outAI4PV}}{N_{hours_{availability_w}/outAI4PV}}$$ Where: • $N_{hours\_availability\_wAI4PV}$ is the number of working hours of the PV plant with AI4PV solutions in place • $N_{hours_{availability_w}/outAI4PV}$ is the number of working hours of the PV plant without AI4PV solutions in place	>5%	1-2-3

6. REFERENCES

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[3] Rubén González (ISOTROL), Louelson Costa (INESC TEC), Christian Verrecchia (EDP NEW), "D4.1 - Validation framework definition".