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D1.6 Final follow-up on KPIs progress on PV reliability, performance and profitability, and grid integration – Public version

T1.5 Follow-up on KPIs progress on PV Reliability, Performance and Profitability and grid integration

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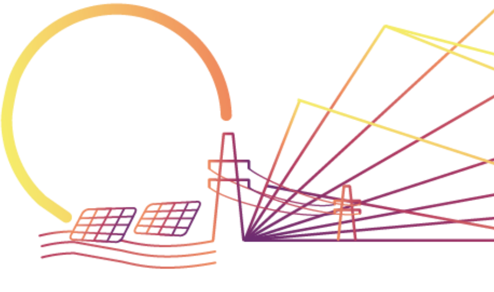

Summary

The purpose of this report is to provide a final-term follow-up on the progress of the **K**ey **P**erformance **I**ndicators (KPIs) considered in the SERENDI-PV project as per task 1.1 of the working package WP1 and publicly shared in D1.1 [1]. These KPIs span the reliability, performance, profitability, and grid integration of solar PV.

The report first recaps the selected KPIs as well as the planned innovations to be developed by the project partners. Then, the main section of the report outlines the project partners' expert opinion on the nature of the impact of these innovations on each KPI. This final-term follow-up is only considered as a hypothesis that will be confirmed by actual measurements at the end of the project.

This deliverable is an output of task T1.5 of WP1 of the SERENDI-PV project.

Document Information

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Document History

Date	Version	Prepared by	Organization	Approved by	Notes
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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This is the second report in a series of two reports that form the output of task 1.5 of working package 1 (WP1) of the SERENDI-PV project. This report constitutes a final-term follow-up, based on demonstration results quantitative assessment of the progress on the SERENDI-PV KPIs.

The purpose of this report is to finalise the assessment of the project innovations and provide quantitative measurements of the innovations impact on the KPIs, following the partners´ opinions about the potential impact of the developed innovations presented in the mid-term report. The introduction first recaps the list of selected KPIs related to solar PV reliability, performance, profitability, and grid integration selected for SERENDI-PV project in T1.1 of WP1 and published as public deliverable D1.1 [2]. It also summarises the innovations and tools that are being developed by the SERENDI-PV project partners for which the impact is monitored. Furthermore, an overview of the survey used to collect expert opinion on the matter is given.

Sections 3 to 8 form the main body of this report. Each section corresponds to one of the six identified KPI categories: performance, reliability, power modelling and forecasting, monitoring, profitability and the grid specific KPIs. These are then divided into sub-sections corresponding to the included KPIs within this category. Each of the sub-sections first defines the KPI in question. Then, it lists the innovations and categorizes them based on whether they have an impact on this KPI or not. Lastly, it discusses in greater detail the measured KPI value for the innovation. The main findings and outlook of this report are concluded in the last section.

1.2 Reference material

The first part of this document is based on another report published earlier as part of the project where more details on the selected KPIs for the scope of SERENDI-PV can be found: **“SERENDI-PV_D1.1 KPIs on state of the art PV reliability, performance, profitability and grid integration_submitted.pdf”** [1]. It is also based on the planned innovations as part of the original SERENDI-PV project proposal.

1.3 Relation to other activities in the project

Table 1.1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within the SERENDI-PV project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1: Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
D1.1	The current deliverable feeds from the defined KPIs as an output of task T1.1 of working package WP1.
D1.5 and D1.9	The current deliverable feeds from the preliminary assessment of possible innovations’ impact on KPIs from mid-term assessment reports.
WP2-6 & WP8	The current deliverable feeds from and to all the innovations developed as part of working packages WP2-WP6 as well as their demonstration as part of WP8. It compiles partners´ opinions on the potential impacts of the developed innovations on the selected KPIs. These impacts will be revised and concluded in another report at the end of the project based on the results from WP8.

WP9	The results presented in this report are strongly linked to the exploitation of the innovations developed in SERENDI-PV. These results have been used as input to develop the business cases for the innovative solutions in the project in D9.12.

1.4 Abbreviation list

Table 1.2 outlines all the abbreviations used throughout the report.

Table 1.2: Abbreviation list

Abbreviation	Meaning
BAPV	Building-attached PV
BIPV	Building-integrated PV
C	Temperature adjustment factor
CAPEX	Capital expenditures
CLS	Controllable local system
CPR	Temperature-corrected performance ratio
DA	Data availability
DSO	Distribution system operator
DQ	Data quality
E_{out}	Output AC electricity
EMS	Energy management system
EPI	Energy performance index
FSS	Forecast skill score
G_{ref}	Reference irradiance
H	Total on-plane radiation
iMsys	Integrated management system
KPI	Key performance indicator
LCoE	Levelised cost of electricity
MAE	Mean absolute error
MBE	Mean bias error
(M)IRR	(Modified) internal rate of return
NPV	Net present value
NWP	Numerical weather prediction
OPEX	Operational expenditures
P_0	Rated DC power
P2P	Peer-to-peer
PF	Profile factor
PO	Observed PV power
PP	Predicted PV power
PPA	Power purchase agreement
PR	Performance ratio
PR_{exp}	Expected performance ratio
PLR	Performance loss rate
PV	Photovoltaics
RMSE	Root mean square error

Abbreviation	Meaning
$RMSE_{ref}$	Reference root mean square error
SoC	State-of-charge
SoH	State-of-health
SR	Soiling ratio
STC	Standard testing conditions
T	Task
T_{mod}	Module temperature
T_{ref}	Reference temperature under STC
TRL	Technology readiness level
TSO	Transmission system opperator
WACC	Weighted average cost of capital
WP	Working package
Y_E	Expected yield
Y_f	Final yield
Y_r	Reference yield

2 Introduction

All the major world regions have witnessed an increase in installed solar PV capacities over the previous years, with solar PV surpassing installed wind capacities in 2021 [3], [4]. This uptake in solar PV installations has been mainly driven by the decreasing costs of the technology as well as the more equal distribution of solar resources worldwide compared to other renewable resources. In anticipation of the major role that solar PV will play in future energy systems, the SERENDI-PV project proposes several innovations to improve the performance and utility-friendliness of solar PV.

Task 1.1 of the SERENDI-PV project identified and compiled a list of KPIs spanning the performance, reliability, power modelling and forecasting, monitoring, and profitability of solar PV systems of different scales. The selected KPIs were deemed the most relevant and informative about the impact of the developed innovations during SERENDI-PV on the different aspects of solar PV performance. Table 2.1 outlines the selected KPIs as per **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1].

Table 2.1: SERENDI-PV project key performance indicators (KPIs)

Category	Key performance indicator	Technical or General KPI
Performance	Performance ratio (PR)	General
	Temperature-corrected performance ratio (CPR)	General
	Soiling ratio (SR)	General
Reliability	Performance loss rate (PLR)	Technical
Power modelling and forecasting	Root mean square error (RMSE)	Technical
	Mean absolute error (MAE)	Technical
	Mean bias error (MBE)	Technical
	Forecast skill score (FSS)	Technical
Monitoring	Energy performance index (EPI)	Technical
	Data availability (DA)	Technical
	Data quality (DQ)	Technical
Profitability	Levelised cost of electricity (LCoE)	General
	Profile factor (PF)	General
	Weighted average cost of capital (WACC)	General
	Net present value (NPV)	General
	(Modified) Internal rate of return ((M)IRR)	General

As part of the original project proposal, a list of existing tools and innovations at a technology readiness level (TRL) of 6-7 are planned to be developed to reach a TRL of 7-8. These developments are part of working packages WP2-6. Their demonstration and integration are part of WP8, where the impacts of such developments on the selected KPIs are monitored. The impacts are then reported as part of this task, T1.5 of WP1. Tables 2.2-2.6 below list all the innovations included in the impact assessment by working package. The innovations are indexed based on the working package number and their order within each package. These indices will be used later when referring to innovations for the sake of brevity. Owners are mentioned using their short names. The full organization name can be found in the legal notice at the beginning of this document.

To conduct the final follow-up, the applicable KPI's were estimated for the innovations based on the measurements received in demonstration and integration WP8. The results often differ from the mid-term report conclusions based on project partners' expert opinions survey about the potential direct as not all KPIs could be measured for innovations. The KPIs were additionally subdivided into technical KPIs and general

KPIs categories. Technical KPIs include the KPIs which have impact on the performance of specific equipment and can be directly measured with existing equipment and standard methods. General KPIs have impact on the overall performance of the PV systems and demand assessment of not only the developed element but of the whole PV system, for such KPIs the direct measurements often are not possible within the scope of the project and the KPIs values were estimated based on technical KPIs and/or additional assumptions.

The rest of the report goes over the selected KPIs by category. Each of the KPIs is first briefly explained as per **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1]. Then, the impact of different innovations on it according to expert opinion is outlined and discussed. Finally, the main findings are highlighted and concluded.

Table 2.2: SERENDI-PV WP2 innovations

ID	Innovation
2.1	Modelling of bifacial PV systems
2.2	Modelling of floating PV systems
2.3	Modelling of small PV systems, including building attached PV (BAPV)
2.4	Modelling of building integrated PV (BIPV) systems, any size
2.5	Modelling of soiling
2.6	Modelling of snow
2.7	Modelling of degradation
2.8	Load profiles generation for self-consumption evaluation
2.9	Modelling of uncertainty and variability and implementation into financial models
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments

Table 2.3: SERENDI-PV WP3 innovations

ID	Innovation
3.1	Specific data analytics for bifacial PV systems
3.2	Specific data analytics for floating PV systems
3.3	Specific data analytics for small PV systems, including BAPV
3.4	Specific data analytics for BIPV systems, any size
3.6	Specific data analytics for vegetation
3.7	Specific data analytics for snow
3.8	Specific data analytics for degradation
3.9	IR imaging data analytics
3.10	Failure detection and diagnosis methods
3.11	Fault detection/diagnosis toolbox for small PV
3.12	PV inverter efficiency characterisation
3.13	Predictive diagnosis of inverter temperature anomalies
3.14	PV inverter digital twin

3.15	PV battery digital twin
3.16	BIPV digital twin
3.17	Quality control system for identification of incorrect data from PV power plants

Table 2.4: SERENDI-PV WP4 innovations

ID	Innovation
4.1	Specific procedures for bifacial PV systems
4.2	Specific procedures for floating PV systems
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory
4.4	New procedures for PV inverters field testing
4.5	Procedure for PV inverters MPPT testing
4.6	Procedure for measuring MPPT efficiency in the field
4.7	Operating conditions measuring kit
4.8	Soiling measurement kit
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV
4.11	capacitive I-V tracer at 1,500V
4.12	New procedures for batteries field testing
4.13	Procedure for measuring ageing rates in PV modules in the field
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field

Table 2.5: SERENDI-PV WP5 innovations

ID	Innovation
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events
5.4	Forecasting applied to bifacial PV systems
5.5	Forecasting applied to floating PV systems
5.6	Forecasting applied to residential PV systems
5.7	Forecasting for spatial averaging and PV aggregation

Table 2.6: SERENDI-PV WP6 innovations

ID	Innovation
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)

6.2	Automated data model integration framework for PV integration and communication in DSO data systems
6.3	Digital twin of the grid with high PV contribution
6.4	Further integration G2V into self-consumption optimisation software
6.5	Implementation of IEC61850 for data communication on MV/LV grid
6.6	Predictive EMS for PV storage self-consumption
6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.

The technical KPIs calculations are presented in the respective WP8 deliverables, this report summarises the findings and provides indexing to the WP8 reports with full information on inputs and calculations for the KPIs. Some of the deliverables were still in draft version, so some figures, tables, and chapters can slightly change.

3 Impact of innovations on reliability KPIs

Only one indicator has been selected in T1.1 [1] as a reliability KPI, which is the performance loss rate (PLR). This KPI is briefly explained here, followed by a summary of partners´ opinions on which innovations impact it (see Table 3.1) and final quantification of the KPI values for applicable innovations. More details about the KPI, the factors that affect it, and its state-of-the-art value can be found in **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1].

Table 3.1: Summary of the impact of SERENDI-PV innovations on reliability KPIs

ID	Innovation	PLR
2.1	Modelling of bifacial PV systems	
2.2	Modelling of floating PV systems	
2.3	Modelling of small PV systems, including building attached PV (BAPV)	
2.4	Modelling of building integrated PV (BIPV) systems, any size	
2.5	Modelling of soiling	
2.6	Modelling of snow	
2.7	Modelling of degradation	X
2.8	Load profiles generation for self-consumption evaluation	
2.9	Modelling of uncertainty and variability and implementation into financial models	
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions	
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments	
3.1	Specific data analytics for bifacial PV systems	X
3.2	Specific data analytics for floating PV systems	X
3.3	Specific data analytics for small PV systems, including BAPV	
3.4	Specific data analytics for BIPV systems, any size	
3.5	Specific data analytics for soiling	X
3.6	Specific data analytics for vegetation	X
3.7	Specific data analytics for snow	X
3.8	Specific data analytics for degradation	X
3.9	IR imaging data analytics	X
3.10	Failure detection and diagnosis methods	
3.11	Fault detection/diagnosis toolbox for small PV	
3.12	PV inverter efficiency characterisation	
3.13	Predictive diagnosis of inverter temperature anomalies	
3.14	PV inverter digital twin	
3.15	PV battery digital twin	
3.16	BIPV digital twin	
3.17	Quality control system for identification of incorrect data from PV power plants	X
4.1	Specific procedures for bifacial PV systems	
4.2	Specific procedures for floating PV systems	
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	
4.4	New procedures for PV inverters field testing	
4.5	Procedure for PV inverters MPPT testing	

4.6	Procedure for measuring MPPT efficiency in the field	
4.7	Operating conditions measuring kit	
4.8	Soiling measurement kit	
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)	
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV	
4.11	capacitive I-V tracer at 1,500V	
4.12	New procedures for batteries field testing	
4.13	Procedure for measuring ageing rates in PV modules in the field	
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)	
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation	
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events	
5.4	Forecasting applied to bifacial PV systems	
5.5	Forecasting applied to floating PV systems	
5.6	Forecasting applied to residential PV systems	
5.7	Forecasting for spatial averaging and PV aggregation	
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)	
6.2	Automated data model integration framework for PV integration and communication in DSO data systems	
6.3	Digital twin of the grid with high PV contribution	
6.4	Further integration G2V into self-consumption optimisation software	
6.5	Implementation of IEC61850 for data communication on MV/LV grid	
6.6	Predictive EMS for PV storage self-consumption	
6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)	
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).	
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.	

3.1 Performance loss rate

The PLR of a PV system is the rate of reduction of its performance over time, usually measured in percent per annum. This is measured at the system and not the module level, which differentiates it from the module degradation rate. Both irreversible module degradation as well as reversible and/or preventable system-level factors are included in the PLR. Recoverable losses, such as those caused by soiling, snow, and shading from vegetation, can potentially be mitigated through changes in operations and maintenance (O&M) activities. On the other hand, nonrecoverable losses, like material degradation, can be quantified to evaluate the risks associated with different technologies in various environments. This distinction is crucial since recoverable and nonrecoverable losses impact the overall PLR metric in different ways [4]. It is calculated as a ratio between the daily, weekly, monthly, or yearly PR of two subsequent years. The CPR can also be used for the calculation.

3.1.1 Impact of WP2 innovations on PLR

The PLR was measured within demonstration WP8 for 'modelling of degradation' (2.7). However, PLR was found not applicable to other innovations including 'modelling bifacial PV systems' (2.1), 'modelling of floating PV systems' (2.2), 'modelling small PV systems including BAPV systems' (2.3), 'modelling of BIPV systems of any size' (2.4), 'modelling of soiling' (2.5), 'modelling of snow' (2.6), 'load profiles generation for self-consumption evaluation' (2.8), 'modelling of uncertainty and variability and implementation into financial models' (2.9).

3.1.1.1 Measured impact

	Innovation name	PLR value	Origin deliverable	Ref
2.7	Modelling of degradation	0.1%	D8.5, Table 6.5	[5]

Despite lack of proof of PLR impact within limited period of demonstration it is identified that better modelling could lead to a better understanding of loss and better preventative measures against PLR as discussed in mid-term report D1.9.

3.1.2 Impact of WP3 innovations on PLR

As part of demonstration WP8 the PLR was measured for 'Specific data analytics for bifacial PV systems' (3.1), 'Specific data analytics for floating PV systems' (3.2), 'Specific data analytics for soiling' (3.5), 'Specific data analytics for snow' (3.6), 'Specific data analytics for degradation' (3.7), 'IR imaging data analytics' (3.9) and 'Quality control system for identification of incorrect data from PV power plants' (3.16).

For other innovations the PLR is not applicable as KPI or could not be measured.

Despite the applicability of the KPI to many of WP3 innovations, this KPI was not measured during demandstration.

3.1.2.1 Measured impact

	Innovation name	PLR value	Origin deliverable	Ref
3.1	Specific data analytics for bifacial PV systems	Implemented**	D8.4, Ch 4.1.3	[6]
3.2	Specific data analytics for floating PV systems	no data*	-	
3.5	Specific data analytics for soiling	no data*	-	
3.6	Specific data analytics for vegetation	Implemented**	D8.4, Ch 4.3.2	[6]
3.7	Specific data analytics for snow	Implemented**	D8.4, Ch 4.3.2	[6]
3.8	Specific data analytics for degradation	Implemented**	D8.4, Ch 4.3.3	[6]
3.9	IR imaging data analytics	1.25%-7.54%	D8.4, Table 4.16	[6]
3.13	Predictive diagnosis of inverter temperature anomalies	91%	D8.4, Ch 4.4.2	[6]
3.17	Quality control system for identification of incorrect data from PV power plants	no data*	-	

* For some of the innovations the KPI was found applicable but could not be demonstrated within the project

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

3.1.3 Impact of WP4 innovations on PLR

For WP4 innovations PLR was found not applicable as KPI or could not be measured as part of demonstration WP8.

3.1.4 Impact of WP5 innovations on PLR

For WP5 innovations PLR was found not applicable as KPI or could not be measured as part of demonstration WP8.

3.1.5 Impact of WP6 innovations on PLR

For WP6 innovations PLR was found not applicable as KPI or could not be measured as part of demonstration WP8.

4 Impact of innovations on power modelling and forecasting KPIs

Four indicators have been selected in D1.1 [1] as power modelling and forecasting KPIs. Power modelling differs from forecasting. The former is a simulation of a PV system performance under previously measured conditions while the latter is based on future forecasts which start with an initial measured or modelled value. The selected KPIs are the root mean square error (RMSE), the mean absolute error (MAE), the mean bias error (MBE), and the forecast skill score (FSS). These are briefly described below, then the effect of SERENDI-PV innovations on them according to expert opinion and quantification based on demonstration is outlined in **¡Error! No se encuentra el origen de la referencia.** and discussed in respective sub-sections. These KPIs are discussed in detail in **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1].

Table 4.1: Summary of the impact of SERENDI-PV innovations on power modelling and forecasting KPIs

ID	Innovation	RMSE	MAE	MBE	FSS
2.1	Modelling of bifacial PV systems	X	X	X	
2.2	Modelling of floating PV systems	X	X	X	
2.3	Modelling of small PV systems, including building attached PV (BAPV)	X	X	X	
2.4	Modelling of building integrated PV (BIPV) systems, any size	X	X	X	
2.5	Modelling of soiling	X	X	X	
2.6	Modelling of snow	X	X	X	
2.7	Modelling of degradation		X	X	
2.8	Load profiles generation for self-consumption evaluation				
2.9	Modelling of uncertainty and variability and implementation into financial models				
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions		X		
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments				
3.1	Specific data analytics for bifacial PV systems			X	
3.2	Specific data analytics for floating PV systems	X		X	
3.3	Specific data analytics for small PV systems, including BAPV				
3.4	Specific data analytics for BIPV systems, any size	X		X	
3.5	Specific data analytics for soiling				
3.6	Specific data analytics for vegetation				
3.7	Specific data analytics for snow				
3.8	Specific data analytics for degradation				
3.9	IR imaging data analytics				
3.10	Failure detection and diagnosis methods				
3.11	Fault detection/diagnosis toolbox for small PV				
3.12	PV inverter efficiency characterisation				
3.13	Predictive diagnosis of inverter temperature anomalies				
3.14	PV inverter digital twin				

3.15	PV battery digital twin				
3.16	BIPV digital twin				
3.17	Quality control system for identification of incorrect data from PV power plants				
4.1	Specific procedures for bifacial PV systems	X			
4.2	Specific procedures for floating PV systems				
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory				
4.4	New procedures for PV inverters field testing	X	X	X	
4.5	Procedure for PV inverters MPPT testing				
4.6	Procedure for measuring MPPT efficiency in the field	X	X	X	
4.7	Operating conditions measuring kit	X	X	X	
4.8	Soiling measurement kit	X	X	X	
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)				
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV				
4.11	capacitive I-V tracer at 1,500V	X	X	X	
4.12	New procedures for batteries field testing	X	X	X	
4.13	Procedure for measuring ageing rates in PV modules in the field	X	X	X	
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	X	X	X	
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)				
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation	X	X	X	X
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events				
5.4	Forecasting applied to bifacial PV systems	X	X	X	
5.5	Forecasting applied to floating PV systems	X	X	X	
5.6	Forecasting applied to residential PV systems				
5.7	Forecasting for spatial averaging and PV aggregation	X	X	X	
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)				
6.2	Automated data model integration framework for PV integration and communication in DSO data systems				
6.3	Digital twin of the grid with high PV contribution				
6.4	Further integration G2V into self-consumption optimisation software		X		
6.5	Implementation of IEC61850 for data communication on MV/LV grid				
6.6	Predictive EMS for PV storage self-consumption				

6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)				
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).				
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.		X		

4.1 Root Mean Square Error

The RMSE is used for both power modelling and power forecasting. This metric is often used to compare a time series of modelled or forecasted values to observed ones. It measures the scatter of the simulation or forecasting model with respect to actual observations. In that sense, the lower the RMSE is, the better the forecasting, with a value of 0 corresponding to a perfect match between a model and reality. The RMSE gives a higher weight to larger errors compared to smaller ones. It is also sensitive to data outliers. The formula used to calculate the RMSE for PV power can be seen **¡Error! No se encuentra el origen de la referencia.**:

$$RMSE_P = \sqrt{\sum_{i=1}^{i=N} \frac{(PP_i - PO_i)^2}{N}}$$

(1)

Where:

- PP_i: modelled or predicted PV power at time step i [kWh]
- PO_i: observed PV power at time step i [kWh]
- i: time step index
- N: sample size, i.e. total number of considered time steps

Other variations of the RMSE include the normalised and relative options. The first normalises the RMSE with respect to the rated power of the PV system, which makes plants of different sizes comparable. The second one divides the RMSE by the average value of observations. Relative RMSE is commonly used in solar resource modelling and is used here for PV power modelling and forecasting.

4.1.1 Impact of WP2 innovations on RMSE

As part of demonstration WP8 the RMSE was measured for most of the WP2 innovations, except for ‘Modelling of degradation’ (2.7), ‘Load profiles generation for self-consumption evaluation’ (2.8), ‘Modelling of uncertainty and variability and implementation into financial models’ (2.9), ‘Analytically tracking uncertainty propagation in financial models with probability density functions’ (1.10), and ‘Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments’ (2.12).

4.1.1.1 Measured impact

	Innovation name		RMSE value	Origin deliverable	Ref
2.1	Modelling of bifacial PV systems	Archelios	22%	D8.5, Table 7.4, 7.5	[5]
		Solargis	5%	D8.5, Table 7.6	

2.2	Modelling of floating PV systems	no mismatch	4.52kW(24.68%)	D8.5, Table 8.1, 8.2	[5]
		new mismatch model	4.43kW(24.17%)		
2.3	Modelling of small PV systems, including building attached PV (BAPV)		no data*	-	-
2.4	Modelling of building integrated PV (BIPV) systems, any size		44.4%	D8.10, Table 3.2	[7]
2.5	Modelling of soiling	3.8 mm	0.65%-3.65%	D8.5, Table 4.1, 4.2, 4.3, 4.4, Figures 4.28, 4.32	[5]
		5 mm	0.65%-3.66%		
2.6	Modelling of snow		no data *	-	-

* For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.1.2 Impact of WP3 innovations on RMSE

RMSE was found applicable for innovations such as ‘Specific data analytics for floating PV systems’ (3.2) and ‘Specific data analytics for BIPV systems, any size’ (3.3).

4.1.2.1 Measured impact

			RMSE value	Origin deliverable	Ref
3.2	Specific data analytics for floating PV systems	KPIs against reference simulation	29.55%	D8.4, Table 4.11	[6]
		KPIs against enhanced simulation using real module orientation data	28.57%		
3.4	Specific data analytics for BIPV systems, any size	Carport Shed	13.05-110.9 (W/m2)	D8.10, Table 3.5	[7]
		Roof	12.55-110.61 (W/m2)		

4.1.3 Impact of WP4 innovations on RMSE

Within the demonstration WP8 RMSE was measured for six innovations from WP4. RMSE was found not applicable for innovations such as ‘Specific procedures for floating PV systems’ (4.2), ‘Hardware in the Loop Platform for testing large inverters in the laboratory’ (4.3), ‘Procedure for PV inverters MPPT testing’ (4.5), ‘Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)’ (4.9), and ‘Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV ’ (4.10).

4.1.3.1 Measured impact

	Innovation name	RMSE value	Origin deliverable	Ref
4.1	Specific procedures for bifacial PV systems	Implemented**	D8.3, Table 1.2	[8]
4.4	New procedures for PV inverters field testing	Implemented**	D8.3, Table 1.6	[8]
4.6	Procedure for measuring MPPT efficiency in the field	0.91%	D8.3, Ch 4.3.2	[8]
4.7	Operating conditions measuring kit	Implemented**	D8.3, Ch 4.2.3	[8]
4.8	Soiling measurement kit	Implemented**	D8.3, Ch 4.1.3	[8]
4.11	capacitive I-V tracer at 1,500V	Implemented**	D8.3, Table 1.2	[8]
4.12	New procedures for batteries field testing	Implemented**	D8.3, Ch 4.4.1	[8]
4.13	Procedure for measuring ageing rates in PV modules in the field	<1%	D8.3, Ch 4.1.5	[8]

4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	<1.5% in Isc, <1% in Voc, <2.5% in Pm	D8.3, Ch 4.2.2	[8]

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

4.1.4 Impact of WP5 innovations on RMSE

RMSE was measured for three innovations from WP4. RMSE was found not applicable for innovations such as ‘Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)’ (5.1), ‘Improved power forecasting in presence of snow, dust, fog, and other extreme events’ (5.3), and ‘Forecasting applied to residential PV systems, and Forecasting for spatial averaging and PV aggregation’ (5.6).

4.1.4.1 Measured impact

	Innovation name		RMSE value	Origin deliverable	Ref
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation		27-35.9%	D8.11, Figure 7.3,7.4	[9]
5.4	Forecasting applied to bifacial PV systems		43-45.5%	D8.11, Ch 14 -	[9]
5.5	Forecasting applied to floating PV systems	1h forecast	21.71-22.85%	D8.11, Table 7.5	[9]
		1d forecast	24.50-24.65%		
5.7	Forecasting for spatial averaging and PV aggregation		4-5.5%	D8.11, Figure 13.2	[9]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.1.5 Impact of WP6 innovations on RMSE

RMSE was found not applicable as KPI for WP6 innovations or could not be measured as part of demonstration within WP8.

4.2 Mean Absolute Error

Similar to the RMSE, the MAE measures the scatter of a model with respect to the observed reality. Again, a value of 0 indicates a perfect match between the model and reality. The higher the MAE is, the less accurate a model is. Unlike the RMSE, the MAE gives equal weights to all errors, irrespective of their size, and is less sensitive to outliers. It can also be normalised to the rated power of the PV system or weighted relative to the average observed value. In general, it is more suited for forecasting applications. The MAE of PV power is calculated as shown below:

$$MAE_P = \frac{1}{N}\sum_{i=1}^{i=N}(PP_i - PO_i) \tag{2}$$

4.2.1 Impact of WP2 innovations on MAE

As part of demonstration WP8 the MAE was measured for most of the WP2 innovations, except for ‘load profiles generation for self-consumption evaluation’ (2.8), ‘Modelling of uncertainty and variability and implementation into financial models‘ (2.9), and ‘Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments‘ (2.11). Although it was impossible to measure the MAE as part of demonstration within the project, in D1.5 it was discussed that developed innovations in modelling of snow (2.6) and modelling of degradation (2.8) should have positive impact on the MAE.

4.2.1.1 Measured impact

	Innovation name		MAE value	Origin deliverable	Ref
2.1	Modelling of bifacial PV systems	Archelios	38%	D8.5, Table 7.4	[5]
		Solargis	3.84%	D8.5, Table 7.6	
2.2	Modelling of floating PV systems	no mismatch	2.97 kW (16.22%)	D8.5, Table 8.2	[5]
		new mismatch model	2.87 kW (15.67%)		
2.3	Modelling of small PV systems, including building attached PV (BAPV)		no data*	-	-
2.4	Modelling of building integrated PV (BIPV) systems, any size		19.6%	D8.10, Table 3.2	[7]
2.5	Modelling of soiling	3.8 mm	0.32%-1.84%	D8.5, Table 4.2,3	[5]
		5 mm	0.32%-1.85%		
2.6	Modelling of snow		26.3W - 329.5W	D8.10 table 5.2, 5.3	[7]
2.7	Modelling of degradation		no data*	-	-
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions		no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.2.2 Impact of WP3 innovations on MAE

For WP3 innovations MAE was found not applicable as KPI or could not be measured as part of demonstration within WP8.

4.2.3 Impact of WP4 innovations on MAE

Within demonstration WP8 MAE was measured for six innovations from WP4. MAE was found not applicable for innovations such as ‘Specific procedures for bifacial PV systems’ (4.1), ‘Specific procedures for floating PV systems’ (4.2), ‘Hardware in the Loop Platform for testing large inverters in the laboratory’ (4.3), ‘Procedure for PV inverters MPPT testing’ (4.5), and ‘Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)’ (4.9), or it was not possible to measure MAE as part of WP8.

4.2.3.1 Measured impact

	Innovation name	MAE value	Origin deliverable	Ref
4.4	New procedures for PV inverters field testing	Implemented**	D8.3, Table 1.6	[8]
4.6	Procedure for measuring MPPT efficiency in the field	0.91%	D8.3, Ch 4.3.2	[8]
4.7	Operating conditions measuring kit	Implemented**	D8.3, Ch 4.2.3	[8]

4.8	Soiling measurement kit	Implemented**	D8.3, Ch 4.1.3	[8]
4.11	capacitive I-V tracer at 1,500V	Implemented**	D8.3, Table 1.2	[8]
4.12	New procedures for batteries field testing	Implemented**	D8.3, Ch 4.4.1	[8]
4.13	Procedure for measuring ageing rates in PV modules in the field	<1%	D8.3, Ch 4.1.5	[8]
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	<1.5% in Isc, <1% in Voc, <2.5% in Pm	D8.3, Ch 4.2.2	[8]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

4.2.4 Impact of WP5 innovations on MAE

RMSE was measured for three innovations from WP4. MAE was found not applicable for innovations such as 'Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)' (5.1), 'Improved power forecasting in presence of snow, dust, fog, and other extreme events' (5.3), and 'Forecasting applied to residential PV systems' (5.6).

4.2.4.1 Measured impact

	Innovation name	MAE value	Origin deliverable	Ref
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation	17-24%	D8.11, Figures 7.3,7.4	[9]
5.4	Forecasting applied to bifacial PV systems	no data*	-	-
5.5	Forecasting applied to floating PV systems	no data*	-	-
5.7	Forecasting for spatial averaging and PV aggregation	2.1-3%	D8.11, Figure 13.2	[9]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.2.5 Impact of WP6 innovations on MAE

MAE was found not applicable as KPI for WP6 innovations or could not be measured as part of demonstration within WP8 except for 'Further integration G2V into self-consumption optimisation software' (6.4) and 'Operation of PV ensuring active power reserve available to provide ancillary services - grid connected' (6.9).

4.2.5.1 Measured impact

	Innovation name	MAE value	Origin deliverable	Ref
6.4	Further integration G2V into self-consumption optimisation software	no data*	-	-
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.	0.03%-3.22%	D8.11 Ch 5.5.3, 5.5.4	[9]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.3 Mean Bias Error

The MBE is a metric used to detect systematic deviations. Thus, it is suitable for assessing the quality of PV power modelling, not forecasting, on a yearly basis or over longer periods. The MBE also indicates the direction of the deviation such that positive MBE values indicate a systematic overestimation, and vice versa. When used for one PV system, it corresponds to the long-term deviation between the mean modelled and observed values. When used for several sites, it reveals systematic deviations in the model used for these sites. Like the RMSE and the MAE, normalised and relative versions of the MBE can also be used. Equations **¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.** show how the MBE of PV power modelling can be calculated.

$$MBE_P = \frac{1}{N}\sum_{i=1}^{i=N} |PP_i - PO_i| = \overline{PP} - \overline{PO}$$

(3)

Where:

$$\overline{PP} = \frac{1}{N}\sum_{i=1}^{i=N} PP_i$$

(4)

4.3.1 Impact of WP2 innovations on MBE

As part of demonstration WP8 the MBE was measured for most of the WP2 innovations, except for ‘Load profiles generation for self-consumption evaluation’ (2.8), ‘Modelling of uncertainty and variability and implementation into financial models’ (2.9), ‘Analytically tracking uncertainty propagation in financial models with probability density functions’ (2.10), and ‘Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments ’ (2.11). Although it was impossible to measure the MAE as part of demonstration within the project, in D1.5 it was discussed that developed innovations in ‘Modelling of snow’ (2.6) and ‘Modelling of degradation’ (2.8) should have positive impact on the MAE.

4.3.1.1 Measured impact

	Innovation name		MBE value	Origin deliverable	Ref
2.1	Modelling of bifacial PV systems	Archelios	-18%	D8.5, Table 7.4	[5]
		Solargis	2%	D8.5, Table 7.6	
2.2	Modelling of floating PV systems	no mismatch	1.78 kW (9.69%)	D8.5, Table 8.2	[5]
		new mismatch model	1.62 kW (8.85%)		
2.3	Modelling of small PV systems, including building attached PV (BAPV)		no data*	-	-
2.4	Modelling of building integrated PV (BIPV) systems, any size		-2.7%	D8.10, Table 3.2	[7]
2.5	Modelling of soiling	3.8 mm	0.17%-(-1.72%)	D8.5, Table 4.2,3	[5]
		5 mm	0.16%-(-1.73%)		
2.6	Modelling of snow		no data*	-	-
2.7	Modelling of degradation		no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.3.2 Impact of WP3 innovations on MBE

MBE was found applicable for innovations such as ‘Specific data analytics for floating PV systems’ (3.2), ‘Specific data analytics for BIPV systems, any size’ (3.4), and ‘Specific data analytics for bifacial PV systems’ (3.1).

4.3.2.1 Measured impact

			MBE value	Origin deliverable	Ref
3.1	Specific data analytics for bifacial PV systems	Measured inverter active power against reference simulation	11.10%	D8.4, Table 4.7	[6]
		QC’d measured inverter active power against reference simulation	6.69%		
3.2	Specific data analytics for floating PV systems	KPIs against reference simulation	29.55%	D8.4, Table 4.11	[6]
		KPIs against enhanced simulation using real module orientation data	28.57%		
3.4	Specific data analytics for BIPV systems, any size	Carport Shed	-12.89-29.64 (W/m2)	D8.10, Table 3.5	[7]
		Roof	-91.4-0.74 (W/m2)		

4.3.3 Impact of WP4 innovations on MBE

Within demonstration WP8 MBE was measured for eight innovations from WP4. MBE was found not applicable for innovations such as ‘Specific procedures for bifacial PV systems’ (4.1), ‘Specific procedures for floating PV systems’ (4.2), ‘Hardware in the Loop Platform for testing large inverters in the laboratory’ (4.3), ‘Procedure for PV inverters MPPT testing’ (4.5), ‘Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)’ (4.9), and ‘Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV’ (4.10), or it was not possible to measure MAE as part of WP8.

4.3.3.1 Measured impact

	Innovation name	MBE value	Origin deliverable	Ref
4.4	New procedures for PV inverters field testing	Implemented**	D8.3, Table 1.6	[8]
4.6	Procedure for measuring MPPT efficiency in the field	0.91%	D8.3, Ch 4.3.2	[8]
4.7	Operating conditions measuring kit	Implemented**	D8.3, Ch 4.2.3	[8]
4.8	Soiling measurement kit	Implemented**	D8.3, Ch 4.1.3	[8]
4.11	capacitive I-V tracer at 1,500V	Implemented**	D8.3, Table 1.2	[8]
4.12	New procedures for batteries field testing	Implemented**	D8.3, Ch 4.4.1	[8]
4.13	Procedure for measuring ageing rates in PV modules in the field	<1%	D8.3, Ch 4.1.5	[8]
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	<1.5% in Isc, <1% in Voc, <2.5% in Pm	D8.3, Ch 4.2.2	[8]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

4.3.4 Impact of WP5 innovations on MBE

RMSE was measured for three innovations from WP4. MAE was found not applicable for innovations such as 'Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)' (5.1), 'Improved power forecasting in presence of snow, dust, fog, and other extreme events' (5.3), and 'Forecasting applied to residential PV systems' (5.6). .

4.3.4.1 Measured impact

	Innovation name	MBE value	Origin deliverable	Ref
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation	3.5-4.2%	D8.11, Figure93,94	[9]
5.4	Forecasting applied to bifacial PV systems	no data*	-	-
5.5	Forecasting applied to floating PV systems	no data*	-	-
5.7	Forecasting for spatial averaging and PV aggregation	0.9-2%	D8.11, Figure 13.2	[9]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.3.5 Impact of WP6 innovations on MBE

MAE was found not applicable as KPI for WP6 innovations or could not be measured as part of demonstration within WP8.

4.4 Forecast Skill Score

The FSS is widely used in meteorology and is applied here to PV power forecasting, not modelling. It compares the inaccuracy (error) of the model in question to a simple reference model. A skill score of 0 means that the evaluated and the reference forecasts have the same accuracy. A negative skill score means that the evaluated forecast performs worse than the reference one while an FSS equal to 1 indicates a perfect forecast. For short-term forecasts, the reference model used is usually persistence. However, more advanced models, like smart persistence, have been suggested recently by Task 16 of the International Energy Agency's Photovoltaic Power Systems Programme [10]. The equation used to calculate the FSS can be seen **¡Error! No se encuentra el origen de la referencia.**, where $RMSE_{ref}$ is the RMSE of a simple reference PV power forecasting model.

$$FSS = \frac{RMSE_{ref} - RMSE}{RMSE_{ref}} \tag{5}$$

4.4.1 Impact of WP2 innovations on FSS

For WP2 innovations FSS was found not applicable as KPI or could not be measured as part of demonstration within WP8.

4.4.2 Impact of WP3 innovations on FSS

For WP3 innovations FSS was found not applicable as KPI or could not be measured as part of demonstration within WP8.

4.4.3 Impact of WP4 innovations on FSS

For WP4 innovations FSS was found not applicable as KPI or could not be measured as part of demonstration within WP8.

4.4.4 Impact of WP5 innovations on FSS

For WP5 innovations FSS was found not applicable as KPI or could not be measured as part of demonstration within WP8 except for ‘PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation’ (5.2). However, even for this innovation the KPI was not measured by the end of project.

4.4.4.1 Measured impact

	Innovation name	FSS value	Origin deliverable	Ref
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation	no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

4.4.5 Impact of WP6 innovations on FSS

For WP6 innovations FSS was found not applicable as KPI or could not be measured as part of demonstration within WP8.

5 Impact of innovations on monitoring KPIs

When it comes to monitoring, uncertainty arises from the different sensors and monitoring devices used in a PV plant. Nevertheless, this is usually not the only source of uncertainty as it can also arise due to other factors like how the modules were installed and how they are maintained. D1.1 [1] selected three parameters as monitoring KPIs, which are the energy performance index (EPI), data availability (DA), and data quality (DQ). The latter two are considered the most relevant when it comes to assessing the quality of a monitoring system. Each of these KPIs is briefly explained, then the expert opinion and quantification on how they are impacted by the SERENDI-PV project innovations is outlined (see **¡Error! No se encuentra el origen de la referencia.**) and discussed in corresponding sub-sections. More details about the KPIs can be found in **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1].

Table 5.1: Summary of the impact of SERENDI-PV innovations on monitoring KPIs

ID	Innovation	EPI	DA	DQ
2.1	Modelling of bifacial PV systems	X		
2.2	Modelling of floating PV systems			
2.3	Modelling of small PV systems, including building attached PV (BAPV)	X		
2.4	Modelling of building integrated PV (BIPV) systems, any size	X		
2.5	Modelling of soiling	X		
2.6	Modelling of snow	X		
2.7	Modelling of degradation			
2.8	Load profiles generation for self-consumption evaluation			
2.9	Modelling of uncertainty and variability and implementation into financial models			
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions			
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments			
3.1	Specific data analytics for bifacial PV systems	X	X	X
3.2	Specific data analytics for floating PV systems	X	X	X
3.3	Specific data analytics for small PV systems, including BAPV			
3.4	Specific data analytics for BIPV systems, any size			
3.5	Specific data analytics for soiling	X	X	X
3.6	Specific data analytics for vegetation			
3.7	Specific data analytics for snow	X	X	X
3.8	Specific data analytics for degradation	X	X	X
3.9	IR imaging data analytics			
3.10	Failure detection and diagnosis methods			
3.11	Fault detection/diagnosis toolbox for small PV			
3.12	PV inverter efficiency characterisation			
3.13	Predictive diagnosis of inverter temperature anomalies			
3.14	PV inverter digital twin	X		
3.15	PV battery digital twin			
3.16	BIPV digital twin	X		

3.17	Quality control system for identification of incorrect data from PV power plants	X	X	X
4.1	Specific procedures for bifacial PV systems	X		
4.2	Specific procedures for floating PV systems			
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory			
4.4	New procedures for PV inverters field testing		X	
4.5	Procedure for PV inverters MPPT testing			
4.6	Procedure for measuring MPPT efficiency in the field		X	
4.7	Operating conditions measuring kit		X	
4.8	Soiling measurement kit		X	
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)			
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV			
4.11	capacitive I-V tracer at 1,500V		X	
4.12	New procedures for batteries field testing		X	
4.13	Procedure for measuring ageing rates in PV modules in the field		X	
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field		X	
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)			
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation			
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events			
5.4	Forecasting applied to bifacial PV systems			
5.5	Forecasting applied to floating PV systems			
5.6	Forecasting applied to residential PV systems			
5.7	Forecasting for spatial averaging and PV aggregation			
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)		X	X
6.2	Automated data model integration framework for PV integration and communication in DSO data systems			
6.3	Digital twin of the grid with high PV contribution			
6.4	Further integration G2V into self-consumption optimisation software			
6.5	Implementation of IEC61850 for data communication on MV/LV grid		X	X
6.6	Predictive EMS for PV storage self-consumption			
6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)			
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).		X	X
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.			

5.1 Energy performance index

The EPI is a ratio between the final energy yield (Y_f), described earlier, and the expected energy yield (Y_E). The Y_E reflects the energy that should have been produced by a PV system over a certain period according to field setup and measurements that are fed into a simulation model. Hence, it is affected by the accuracy of the model used. The EPI can be used to compare plants if the same model is used for the calculation of Y_E, or to detect flaws in a plant operation if the EPI is much lower than 1. Equation **¡Error! No se encuentra el origen de la referencia.** shows how the EPI is calculated.

$$EPI = \frac{Y_f}{Y_E} \tag{6}$$

Where:

$$Y_E = \frac{PR_{exp}}{Y_r} \tag{7}$$

Such that:

- PR_{exp}: expected performance ratio according to plant characteristics and climatic conditions
- Y_r: reference yield [kWh/kW$_p$]

5.1.1 Impact of WP2 innovations on EPI

EPI was found not applicable for innovations such as 'Modelling of floating PV systems' (2.2), 'Modelling of degradation' (2.7),'Load profiles generation for self-consumption evaluation' (2.8), 'Modelling of uncertainty and variability and implementation into financial models' (2.9), 'Analytically tracking uncertainty propagation in financial models with probability density functions' (2.10), and 'Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments' (2.11).

5.1.1.1 Measured impact

	Innovation name		EPI value	Origin deliverable	Ref
2.1	Modelling of bifacial PV systems	Archelios	122.3%	D8.5, Table 7.4	[5]
		Solargis	98.1%	D8.5, Table 7.6	
2.3	Modelling of small PV systems, including building attached PV (BAPV)		no data*	-	-
2.4	Modelling of building integrated PV (BIPV) systems, any size		102.8%	D8.10, Table 3.2	[7]
2.5	Modelling of soiling		no data*	-	-
2.6	Modelling of snow		no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

5.1.2 Impact of WP3 innovations on EPI

EPI was found not applicable for innovations such as 'Specific data analytics for small PV systems, including BAPV' (3.3), 'Specific data analytics for BIPV systems, any size' (3.4), 'Specific data analytics for vegetation' (3.6), 'IR imaging data analytics' (3.9), 'Failure detection and diagnosis methods' (3.10), 'Fault detection/diagnosis toolbox for small PV' (3.11), 'PV inverter efficiency characterisation' (3.12), 'Predictive diagnosis of inverter temperature anomalies' (3.13), and 'PV battery digital twin' (3.15).

5.1.2.1 Measured impact

	Innovation name	EPI value	Origin deliverable	Ref
3.1	Specific data analytics for bifacial PV systems	no data*	-	-
3.2	Specific data analytics for floating PV systems	no data*	-	-
3.5	Specific data analytics for soiling		D8.4, Ch 4.3.2	[6]
3.7	Specific data analytics for snow	no data*	-	-
3.8	Specific data analytics for degradation		D8.4, Ch 4.3.3	-
3.14	PV inverter digital twin	no data*	D8.8, Ch 4.2.2	[11]
3.16	BIPV digital twin	97%**	D8.8, Ch 4.3.2	[11]
3.17	Quality control system for identification of incorrect data from PV power plants	no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

**For the whole demonstration period considering measured environmental conditions (GPOA and PV module temperature) as input, improving the EPI of 111% achieved by the non-calibrated BIPV model

5.1.3 Impact of WP4 innovations on EPI

For WP4 innovations EPI was found not applicable as KPI or could not be measured as part of demonstration within WP8.

5.1.4 Impact of WP5 innovations on EPI

For WP5 innovations EPI was found not applicable as KPI or could not be measured as part of demonstration within WP8.

5.1.5 Impact of WP6 innovations on EPI

For WP6 innovations EPI was found not applicable as KPI or could not be measured as part of demonstration within WP8.

5.2 Data Availability

Simply put, data availability is the fraction of time for which monitoring data is available relative to the total monitoring time of a system. The lower the number of missing values is, the better the KPI is. For an individual sensor, the data recorded is logged separately. Then, to calculate the data availability for the entire system, the availability of one sensor is multiplied by the availability of the measurement in question from all the sensors used.

5.2.1 Impact of WP3 innovations on DA

DA was found applicable for innovations such as 'Specific data analytics for bifacial PV systems' (3.1), 'Specific data analytics for floating PV systems' (3.2), 'Specific data analytics for soiling' (3.5), 'Specific data analytics for snow' (3.7), 'Specific data analytics for degradation' (3.8), 'Quality control system for identification of incorrect data from PV power plants' (3.17)..

5.2.1.1 Measured impact

	Innovation name	DA value	Origin deliverable	Ref
3.1	Specific data analytics for bifacial PV systems	no data*	-	-
3.2	Specific data analytics for floating PV systems	no data*	-	-
3.5	Specific data analytics for soiling		D8.4, Ch 4.3.2	[6]
3.7	Specific data analytics for snow	no data*	-	-
3.8	Specific data analytics for degradation	no data*	-	-
3.17	Quality control system for identification of incorrect data from PV power plants	no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

5.2.2 Impact of WP4 innovations on DA

DA was found not applicable for innovations such as ‘Specific procedures for floating PV systems’ (4.2), ‘Hardware in the Loop Platform for testing large inverters in the laboratory’ (4.3), ‘Procedure for PV inverters MPPT testing’ (4.5), ‘Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)’ (4.9), and ‘Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV’ (4.10)..

5.2.2.1 Measured impact

	Innovation name	DA value	Origin deliverable	Ref
4.1	Specific procedures for bifacial PV systems	Implemented**	D8.3, Table 1.2	[8]
4.4	New procedures for PV inverters field testing	Implemented**	D8.3, Table 1.6	[8]
4.6	Procedure for measuring MPPT efficiency in the field	0.91%	D8.3, Ch 4.3.2	[8]
4.7	Operating conditions measuring kit	Implemented**	D8.3, Ch 4.2.3	[8]
4.8	Soiling measurement kit	Implemented**	D8.3, Ch 4.1.3	[8]
4.11	capacitive I-V tracer at 1,500V	Implemented**	D8.3, Table 1.2	[8]
4.12	New procedures for batteries field testing	Implemented**	D8.3, Ch 4.4.1	[8]
4.13	Procedure for measuring ageing rates in PV modules in the field	<1%	D8.3, Ch 4.1.5	[8]
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	<1.5% in Isc, <1% in Voc, <2.5% in Pm	D8.3, Ch 4.2.2	[8]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

5.2.3 Impact of WP6 innovations on DA

DA was found not applicable for innovations such as ‘Automated data model integration framework for PV integration and communication in DSO data systems’ (6.2), ‘Digital twin of the grid with high PV contribution’ (6.3), ‘Further integration G2V into self-consumption optimisation software’ (6.4), ‘Predictive EMS for PV storage self-consumption’ (6.6), ‘Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)’ (6.7), and ‘Operation of PV ensuring active power reserve available to provide ancillary services - grid connected’ (6.9).

5.2.3.1 Measured impact

	Innovation name	DA value	Origin deliverable	Ref
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)	no data*	-	-
6.5	Implementation of IEC61850 for data communication on MV/LV grid	Implemented**	D8.12, CH 5.3.1	[12]
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry)	Implemented**	D8.12, Ch 5.5	[12]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

5.3 Data Quality

Data measured by sensors usually passes through a filtering system first to eliminate any outliers or false values. In that sense, data quality (DQ) could be reflected by the number of measurements discarded by the filtering system with respect to the total number of measurements recorded by the monitoring system. However, this depends on the quality of the filtering system as well. Hence, it can only be used for plant inter-comparison if the same filtering system is employed by all the plants in question.

5.3.1 Impact of WP2 innovations on DQ

The innovation owners expect that there is no impact from these innovations on data quality.

5.3.2 Impact of WP3 innovations on DQ

Some of the owners of ‘Specific data analytics for bifacial PV systems’ (3.1), foresee an impact from this innovation on data quality. The significance of the impact depends on regional characteristics, irradiation levels, and system topography.

Some partners expect a positive and significant impact on ‘Data quality considering specific data analytics for floating PV systems’ (3.2). In addition, a partner has identified an effect on DQ considering innovations of ‘Specific data analytics for floating PV systems’ (3.2), ‘Specific data analytics for soiling’ (3.5), ‘Specific data analytics for snow’ (3.7), ‘Specific data analytics for degradation’ (3.8), and ‘Quality control system for identification of incorrect data from PV power plants’ (3.17)..

5.3.2.1 Measured impact

	Innovation name	DQ value	Origin deliverable	Ref
3.1	Specific data analytics for bifacial PV systems	no data*	-	-
3.2	Specific data analytics for floating PV systems	no data*	-	-
3.5	Specific data analytics for soiling	no data*	-	-
3.7	Specific data analytics for snow	no data*	-	-
3.8	Specific data analytics for degradation	no data*	-	-
3.17	Quality control system for identification of incorrect data from PV power plants	no data*	-	-

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

5.3.3 Impact of WP4 innovations on DQ

The innovations are deemed to be non-influential when it comes to data quality, according to all owners of innovations.

5.3.4 Impact of WP5 innovations on DQ

None of the innovation owners or project partners expect forecasting innovations from WP5 to have an impact on data quality.

5.3.5 Impact of WP6 innovations on DQ

DQ was found not applicable for innovations such as ‘Automated data model integration framework for PV integration and communication in DSO data systems’ (6.2), ‘Digital twin of the grid with high PV contribution ’ (6.3), ‘Further integration G2V into self-consumption optimisation software’ (6.4), ‘Predictive EMS for PV storage self-consumption’ (6.6), ‘Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)’ (6.7), and ‘Operation of PV ensuring active power reserve available to provide ancillary services - grid connected’ (6.9). .

5.3.5.1 Measured impact

	Innovation name	DQ value	Origin deliverable	Ref
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)	no data*	-	-
6.5	Implementation of IEC61850 for data communication on MV/LV grid	Implemented**	D8.12, Ch 5.3.1	[12]
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry)	Implemented**	D8.12, Ch 5.5	[12]

*For some of the innovations the KPI was found applicable but could not be demonstrated within the project

** For some of the innovations the exact value for KPI is not defined, but related information is discussed in the document.

6 Impact of innovations on performance KPIs

Performance KPIs include the performance ratio (PR), the temperature-corrected performance ratio (CPR), and the soiling ratio (SR). These KPIs help to capture and differentiate the factors that can affect the performance of solar PV plants. This section first briefly explains each KPI as per T1.1, then outlines the expected impacts of SERENDI-PV innovations on each of these KPIs according to expert opinion and quantification based on demonstrations. **¡Error! No se encuentra el origen de la referencia.** summarises which innovations affect performance KPIs. More detailed information about the KPIs, their influencing factors, and their state-of-the-art values can be found in **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1].

Table 6.1: Summary of the impact of SERENDI-PV innovations on performance KPIs

ID	Innovation	PR	CPR	SR
2.1	Modelling of bifacial PV systems	X	X	
2.2	Modelling of floating PV systems	X	X	
2.3	Modelling of small PV systems, including building attached PV (BAPV)	X	X	
2.4	Modelling of building integrated PV (BIPV) systems, any size	X	X	
2.5	Modelling of soiling	X	X	
2.6	Modelling of snow	X	X	
2.7	Modelling of degradation			
2.8	Load profiles generation for self-consumption evaluation			
2.9	Modelling of uncertainty and variability and implementation into financial models			
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions			
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments			
3.1	Specific data analytics for bifacial PV systems			
3.2	Specific data analytics for floating PV systems			
3.3	Specific data analytics for small PV systems, including BAPV			
3.4	Specific data analytics for BIPV systems, any size			
3.5	Specific data analytics for soiling	X	X	X
3.6	Specific data analytics for vegetation			
3.7	Specific data analytics for snow			
3.8	Specific data analytics for degradation			
3.9	IR imaging data analytics	X	X	
3.10	Failure detection and diagnosis methods	X	X	
3.11	Fault detection/diagnosis toolbox for small PV			
3.12	PV inverter efficiency characterisation			
3.13	Predictive diagnosis of inverter temperature anomalies	X	X	
3.14	PV inverter digital twin	X	X	
3.15	PV battery digital twin			
3.16	BIPV digital twin	X	X	
3.17	Quality control system for identification of incorrect data from PV power plants			

4.1	Specific procedures for bifacial PV systems			
4.2	Specific procedures for floating PV systems			
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	X	X	
4.4	New procedures for PV inverters field testing	X	X	
4.5	Procedure for PV inverters MPPT testing			
4.6	Procedure for measuring MPPT efficiency in the field	X	X	
4.7	Operating conditions measuring kit			
4.8	Soiling measurement kit	X	X	X
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)			
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV			
4.11	capacitive I-V tracer at 1,500V	X	X	
4.12	New procedures for batteries field testing	X	X	
4.13	Procedure for measuring ageing rates in PV modules in the field	X	X	
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	X	X	
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)			
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation			
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events			
5.4	Forecasting applied to bifacial PV systems			
5.5	Forecasting applied to floating PV systems			
5.6	Forecasting applied to residential PV systems			
5.7	Forecasting for spatial averaging and PV aggregation			
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)			
6.2	Automated data model integration framework for PV integration and communication in DSO data systems			
6.3	Digital twin of the grid with high PV contribution			
6.4	Further integration G2V into self-consumption optimisation software			
6.5	Implementation of IEC61850 for data communication on MV/LV grid			
6.6	Predictive EMS for PV storage self-consumption			
6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)			
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).			
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.			

6.1 Performance ratio

The performance ratio is one of the most widely used performance metrics for solar PV plants. It is a ratio between the final yield and the reference one. The reference yield (Yr) is the total in-plane radiation (H) relative to the reference irradiance (Gref), which is 1000 W/m2 under standard testing conditions (STC). The final yield (Yf) is the actual output AC energy from the PV array (Eout) divided by its peak DC power (P0). In that sense, the PR accounts for both array losses, like shading and soiling, as well as system losses, like inverter losses during the conversion from DC to AC. The PR can be calculated at the inverter level or the delivery point. In SERENDI-PV, high-accuracy ground measurement instruments as well as quality-controlled solar radiation data are used to calculate the PR yearly at the delivery point. The formula below shows how the PR is calculated:

$$\boldsymbol{PR = \frac{Y_f}{Y_r} = \frac{E_{out}}{P_0} / \frac{H}{G_{ref}}} \tag{8}$$

Many of the SERENDI-PV project innovations are expected to have an impact on the PR. PR can be affected through the innovations impact on the PV system design and overall system efficiency improvements or due to improved operation of existing system and increase of the system availability. The impact of influential innovations is discussed in more detail below.

6.1.1 Impact of WP2 innovations on PR

PR was found applicable for most of innovations in WP2. The WP2 combines numerous innovations of modelling methods for different aspects of PV system operation. Proper modelling allows for better perception of the local conditions on the actual system performance and proactive measures to adapt the PV system design to reduce possible impact of local environment. The table 6.2 presents an example of factors affecting the PV system performance and its impact.

Table 6.2: Summary table for a Yield Assessment with the contribution of each factor along the modelling chain and relative uncertainty [13]

Factor	Uncertainty	Value	Gains/loss	PR
	%	kWh/m^2	%	%
global irradiation on horizontal plane	4	1248		
irradiation on module plane	2.5	1448	16	
shading				
horizon shading	0.5	1445	-0.2	100
row shading	2	1422	-1.7	98.3
object shading	3	1422	0	98.3
soiling	0.5	1414	-0.5	97.9
deviations from STC				
reflection losses	0.5	1376	-2.7	95.2
	%	kWh/kWp	%	%
spectral losses	0.5	1363	-1	94.3
irradiation-dependent losses	0.8	1342	-1.5	92.9
temperature-dependent losses	1	1309	-2.5	90.5
mismatch losses	0.5	1298	-0.8	89.8
Dc cable losses	0.5	1287	-0.8	89.1
inverter losses	1.5	1272	-1.2	88
inverter power limitation	0.5	1272	-0.1	88

additional consumption	0.5	1270	-0.1	87.9
AC cable losses low voltage	0.5	1265	-0.4	87.5
Transformer medium voltage	0.5	1253	-0.9	86.7
Ac cable losses medium voltage	0.5	1252	-0.1	86.6
Transformer high voltage	0	1252	0	86.6
Total	6.5	1252		86.6

Modelling may allow to minimise the shading losses via adjusting row spacing and avoiding use of areas shaded by nearby objects, proper design of cabling and inverter's location may help to reduce mismatch and cabling losses in the system. However, it will not lead to elimination or substantial reduction of the abovementioned losses due to natural limitations, the project expert foresee that the general modelling will lead to maximum 5-10% reduction of these losses.

More specific modelling innovations, snowing or soiling innovations, will help to improve design measures to minimise impact of these special factors. In these cases impact may be higher and the losses reduction could reach 50% thanks to secured maintenance possibilities and preventive measures (optimised tilt angle).

It was found that innovations Modelling of degradation (2.7), Load profiles generation for self-consumption evaluation (2.8), Modelling of uncertainty and variability and implementation into financial models (2.9), Analytically tracking uncertainty propagation in financial models with probability density functions (2.10), Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments (2.10), have no direct or indirect impact on PV system PR.

6.1.1.1 Measured impact

The impact of innovations on PR could not be directly measured with existing demonstrators. Naturally the impact of the innovations will vary from location to location due to many factors affected by climate conditions and environment at the specific PV systems locations. The impact on PR was calculated for generic case of PV system provided by Fraunhofer ISE and used in IEA PVPS publications (table6.2).

	Innovation name	Affected losses impact on PR	Loss reduction from innovation	PR increase
2.1	Modelling of bifacial PV systems	-5.7%	Maximum 5%-10%	0.329% to 0.658%
2.2	Modelling of floating PV systems	-5.7%	Maximum 5%-10%	0.329% to 0.658%
2.3	Modelling of small PV systems, including building attached PV (BAPV)	-5.7%	Maximum 5%-10%	0.329% to 0.658%
2.4	Modelling of building integrated PV (BIPV) systems, any size	-5.7%	Maximum 5%-10%	0.329% to 0.658%
2.5	Modelling of soiling	-0.5%	<50%	0.289%
2.6	Modelling of snow	-2.9% [14]	<50%	1.674%

In all cases the WP2 modelling innovations have limited impact on the PV system PR.

6.1.2 Impact of WP3 innovations on PR

It is considered that better analysis may lead to proper and timely maintenance to prevent uncontrollable failure and therefore the reduction of PR. Proactive maintenance will lead to higher availability of PV system and higher PR. At the same time impact on PR will be factor of economical optimisation and logistics limitations. The experience shows that in certain cases immediate maintenance to fix the fault is not performed by PV system owners due to cost or availability of service. In this case we assume that the owners fix every fault immediately to maximise the PV system output. PR found applicable for all innovations except for Quality control system for identification of incorrect data from PV power plants. However, this impact could only be demonstrated for the innovation appearing in the table below.

6.1.2.1 Measured impact

The innovations impact on the PR is estimated based on 3 parameters: 'Impact on performance' – impact of the faults on the system energy output considering current failure rate, and 'Improvement of the contribution' – reduction of the uncontrollable failure rates due to innovations.

	Innovation name	Reference deliverable	Impact on performance	Improvement of the contribution	Improvement of PR
3.5	Specific data analytics for soiling	D8.4 section 4.3.2	Up to 20%*	Reduction of 37%	5%
3.9	IR imaging data analytics				
3.10	Failure detection and diagnosis methods for large PV plants	D8.4 section	Up to 2%*	Reduction of 95%	1.615%
3.13 3.14	PV inverter digital twin and Predictive diagnosis of inverter temperature anomalies	D8.8 section 4.2.3 ad D8.4 section 4.4.2	Up to 2%**	Reduction of 25%	0.425%
3.16	BIPV digital twin	D8.8 section 4.3.2	Up to 10%**	Reduction of 75%	5.625%

*Based on demonstration results

**Based on consortium experience

6.1.3 Impact of WP4 innovations on PR

It is explained that PR can be improved through faster detection and fixing the faults. Similarly to WP3 innovations faster fault detection and proactive maintenance will lead to higher availability of PV system and higher PR. At the same time impact on PR will be factor of economical optimisation and logistics limitations. The experience shows that in certain cases immediate maintenance to fix the fault is not performed by PV system owners due to cost or availability of service. In this case we assume that the owners fix every fault immediately to maximise the PV system output.

6.1.3.1 Measured impact

The innovations impact on the PR is estimated based on 3 parameters: 'Current failure rate' – occurrence of fault without proposed innovation, 'Impact on performance' – impact of the faults on the system PR, and 'Improvement of the contribution' – reduction of the uncontrollable failure rates due to innovations.

	Innovation name	Current failure rate	Impact on performance	Improvement of the contribution	Improvement of PR

4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	70% of occurrence of lower efficiency rates	0.5% lower efficiency, 0.5% lower production	50% recovery	0.18%
4.4	New procedures for PV inverters field testing	70%	0.5% lower efficiency, 0.5% lower production	50% recovery	0.18%
4.6	Procedure for measuring MPPT efficiency in the field	5% of occurrence of non-optimized MPPT algorithms	0.4% of impact in production	100% of recovery	0.02%
4.8	Soiling measurement kit		Average 2% Worst case 7% of loss	+50% more detection capabilities + automatic diagnosis &campaign optimization	Average: 0.8% Worst case: 4%
4.13	Procedure for measuring ageing rates in PV modules in the field	50% of the modules will present early degradation issues: cracks, delamination, hotspots	2% additional degradation rate	5% recovery through contract claims	0.05%
4.11	Capacitive I-V tracer at 1,500V	1) 20% of modules with power over declared 2) 100% of testing campaigns	1) 1.5% lower power 2) 0.2% of project income in testing campaigns	1) 30% recovery 2) 25%-60% cost reduction	1) 0.09% 2) 0.08%
4.11	Batteries field testing	Estimated 30%	Estimated 0.5%	30% recovery	0.05%
4.14	I-V curve of bifacial PV modules in the field	20% of modules with overdeclared power	1.5% lower power	50% recovery	0.15%

6.1.4 Impact of WP5 innovations on PR

PR was not found applicable to WP5 innovations, as better forecast of PV production naturally does not influence the module performance.

6.1.5 Impact of WP6 innovations on PR

PR was not found applicable to WP6 innovations.

6.2 Temperature-corrected performance ratio

The temperature-corrected performance ratio is also known as PR at STC or DC-corrected PR. It utilises a similar equation as the one used for PR, except that the reference yield is corrected for temperature variations. The purpose of this correction is to account for the deviation of the actual module temperature on-site from the reference one under STC. This makes the PR of PV plants in different climatic conditions comparable. Equation (9) shows how the CPR is calculated:

$$\boldsymbol{CPR = \frac{Y_f}{Y_r} = \frac{E_{out}}{P_0} / \frac{H}{G_{ref} \cdot C}} \tag{9}$$

Where:

- C: temperature adjustment factor, calculated as follows:

$$\boldsymbol{C = 1 + \gamma \cdot (T_{mod} - T_{ref})} \tag{10}$$

Where:

- γ: relative maximum-power temperature coefficient [°C^{-1}]
- T_{mod}: module temperature [°C]
- T_{ref}: reference temperature under STC [25°C]

Since the PR at STC is a variation of the PR, most of the innovations with a potential impact on the latter are also expected to influence the former, and vice versa. **¡Error! No se encuentra el origen de la referencia.** summarised information on influential and non-influential innovations when it comes to the PR at STC.

6.2.1 Impact of WP2-6 innovations on CPR

Impact of the WP2-6 innovations on the PR originates from improved design of the PV system allowing for reduction of the losses and from improved fault detection and proactive maintenance allowing for increased availability of the system. This impact must be uniform for the whole range of operating temperatures of the system and thus the impact on CPR will be same as observed for PR and discussed in paragraph 6.1 of this report.

6.3 Soiling ratio

The soiling ratio is used to reflect the effect of soiling on the performance and compare PV plants in different operating conditions with different soiling degrees. It is a ratio between the actual power output of a soiled device and its expected power output if it is clean. For this purpose, two reference devices are used. A soiled PV cell or module, representative of the PV plant conditions, and a clean one, which is maintained via regular manual or automatic cleaning. The maximum power output as well as the temperature of both devices are then monitored. Alternatively, the energy output could be used to avoid errors due to calibration misalignment.

When it comes to the impact of SERENDI-PV innovations on the SR, **¡Error! No se encuentra el origen de la referencia.** outlined all the innovations and whether they are expected to be influential or not by the project partners. Influential innovations are discussed in more detail below.

6.3.1 Impact of WP2 innovations on SR

The owners of innovations believe that WP2 innovations do not influence SR, even modelling of soiling do not affect this KPI.

6.3.2 Impact of WP3 innovations on SR

The innovation owners have identified that only ‘Specific data analytics for soiling’ innovation may have an impact on the soiling ratio among WP3 innovations, but the soiling ratio was not measured within its demonstration.

6.3.3 Impact of WP4 innovations on SR

The soiling measurement kit and algorithm application to 67 MWp PV plant allowed the operator to reduce soiling losses from 8.7 GWh/year to 3.95 GWh/year, what represented 650 k€/year (already including the cost of the cleaning campaigns). Soiling estimation difference vs a reference item in did not exceed 0.7% in terms of Isc (short-circuit current) and 0.9% in terms of power output.

Actual SR value varies over time and cannot be proper KPI for this Innovation,

6.3.3.1 Measured impact

	Innovation name	SR value error	Origin deliverable	Ref
4.8	Soiling measurement kit	0.7-0.9% >90% availability	D8.4	[6]

6.3.4 Impact of WP5-6 innovations on SR

It is understood that SR is not directly applicable to WP5 innovations. In addition, none of the owners of WP6 innovations or project partners expect them to influence the SR.

7 Impact of innovations on profitability KPIs

The profitability of a PV system is affected by both the costs incurred and the performance of the system. Thus, using capital and operational expenditures alone to compare PV plants does not capture the whole picture as they do not take into consideration how well the plants perform or for how long. D1.1 [1] selected five KPIs that better reflect the profitability of PV plants while accounting for their operational conditions. These are the levelised cost of electricity (LCoE), the net present value (NPV), and the modified internal rate of return (MIRR). Other metrics like the weighted average cost of capital (WACC), and the profile factor (PF) were also selected. These KPIs are briefly described, then the quantification of the expected impact of SERENDI-PV innovations on them is summarised (see **¡Error! No se encuentra el origen de la referencia.**) and discussed. For more details on the KPIs, the **"D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration"** [1] can be consulted.

Table 7.1: Summary of the impact of SERENDI-PV innovations on performance KPIs

ID	Innovation	LCoE	PF	WACC	NPV	M(IRR)
2.1	Modelling of bifacial PV systems	X		X	X	
2.2	Modelling of floating PV systems	X		X	X	
2.3	Modelling of small PV systems, including building attached PV (BAPV)	X		X	X	
2.4	Modelling of building integrated PV (BIPV) systems, any size	X		X	X	
2.5	Modelling of soiling	X		X	X	
2.6	Modelling of snow	X		X	X	
2.7	Modelling of degradation	X		X	X	
2.8	Load profiles generation for self-consumption evaluation	X		X	X	
2.9	Modelling of uncertainty and variability and implementation into financial models	X		X	X	
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions	X		X	X	
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments	X		X	X	
3.1	Specific data analytics for bifacial PV systems	X		X	X	
3.2	Specific data analytics for floating PV systems	X		X	X	
3.3	Specific data analytics for small PV systems, including BAPV	X		X	X	
3.4	Specific data analytics for BIPV systems, any size	X		X	X	
3.5	Specific data analytics for soiling	X		X	X	
3.6	Specific data analytics for vegetation	X		X	X	
3.7	Specific data analytics for snow	X		X	X	
3.8	Specific data analytics for degradation	X		X	X	
3.9	IR imaging data analytics	X		X	X	
3.10	Failure detection and diagnosis methods	X		X	X	
3.11	Fault detection/diagnosis toolbox for small PV	X		X	X	
3.12	PV inverter efficiency characterisation	X		X	X	

3.13	Predictive diagnosis of inverter temperature anomalies	X		X	X	
3.14	PV inverter digital twin	X		X	X	
3.15	PV battery digital twin	X		X	X	
3.16	BIPV digital twin	X		X	X	
3.17	Quality control system for identification of incorrect data from PV power plants					
4.1	Specific procedures for bifacial PV systems					
4.2	Specific procedures for floating PV systems					
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	X		X	X	
4.4	New procedures for PV inverters field testing	X		X	X	
4.5	Procedure for PV inverters MPPT testing					
4.6	Procedure for measuring MPPT efficiency in the field	X		X	X	
4.7	Operating conditions measuring kit	X		X	X	
4.8	Soiling measurement kit	X		X	X	
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)					
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV					
4.11	capacitive I-V tracer at 1,500V	X		X	X	
4.12	New procedures for batteries field testing	X		X	X	
4.13	Procedure for measuring ageing rates in PV modules in the field	X		X	X	
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	X		X	X	
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)		X			
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation					
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events					
5.4	Forecasting applied to bifacial PV systems					
5.5	Forecasting applied to floating PV systems					
5.6	Forecasting applied to residential PV systems		X			
5.7	Forecasting for spatial averaging and PV aggregation					
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)		X		X	
6.2	Automated data model integration framework for PV integration and communication in DSO data systems					
6.3	Digital twin of the grid with high PV contribution					
6.4	Further integration G2V into self-consumption optimisation software	X				
6.5	Implementation of IEC61850 for data communication on MV/LV grid					
6.6	Predictive EMS for PV storage self-consumption	X			X	

6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)					
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).					
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.					

7.1 Levelised cost of electricity

The LCoE distributes the lifecycle costs of a solar PV system over the generated electricity during its anticipated useful lifetime. It is expressed in terms of €/kWh, where the cost is discounted to the initial year of investment to obtain a single value in terms of the currency of the base year. There are different formulae with varying complexity used to calculate the LCoE. However, a relatively simple one has been chosen in D1.1 [1] to calculate it for all types and sizes of solar PV systems in the SERENDI-PV project. This formula is as shown below:

$$LCoE_N = \frac{CAPEX_0 + \sum_{i=1}^{N} \frac{OPEX_i + T_i}{(1+d)^i}}{\sum_{i=1}^{N} \frac{E_i}{(1+d)^i}} \tag{11}$$

Where:

- $LCoE_N$: the calculated LCoE for a system with a theoretical lifetime of N years [$€_{\text{base year}}$/kWh]
- $CAPEX_0$: capital expenditures for year 0 [€]
- $OPEX_i$: operational expenditures for year i [€]
- T_i: taxes and other related payments for year i [€]
- E_i: electricity produced during year i [kWh]
- d: discount rate [%]
- N: theoretical system lifetime [years]

Many SERENDI-PV innovations are deemed to have an impact on the LCoE of solar PV systems. A sensitivity analysis looking into the main parameters influencing LCoE showed that besides yield (local solar resource available and efficiency of resource conversion), the second most significant parameter influencing the LCoE is the WACC (the after-tax discount rate mentioned in the previous formula); with a sensitivity almost as high as the solar resource available [15] The **¡Error! No se encuentra el origen de la referencia.** summarised impact of innovations on LCoE. The influential factors are further discussed below.

7.1.1 Impact of WP2 innovations on LCoE

It is identified that WP2 innovations may affect LCoE in two different ways. On one hand, improved modelling of the PV system may allow for better consideration of the environment impact and design adaptation to reduce environment related losses as discussed in paragraph 6.1. On another hand, improved modelling methods will contribute to reduced uncertainty at the project preparation stage, and better bankability of the project, lower risks and consequently lower WACC compared to projects with higher uncertainty.

As discussed in chapter 7.3 reduced uncertainty of lon-term project planning and lower risks of the project contribute to reduced WACC, but there is no direct formula to convert uncertainty reduction to WACC decrease. Furthermore, project WACC depends on many other non-technical parameters and may substantially vary over time and region to region. For illustrative reasons the LCoE calculations for WACC recline contribution are made for 1% decline from 10% WACC to 9% WACC for major modelling innovations Modelling of bifacial PV systems (2.1), Modelling of floating PV systems (2.2), Modelling of small PV systems, including building attached PV (BAPV) (2.3), Modelling of building integrated PV (BIPV) systems, any size (2.4). For other innovation, improving modelling of certain aspects of the system, the calculations are made for 0.25% recline of WACC from 10% to 9.75%, considering that the individual innovations have limited impact on overall system operation uncertainty.

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.1.1.1 Measured impact

	Innovation name	Contributor	LCoE reduction
2.1	Modelling of bifacial PV systems	PR	0.328% to 0.654%
		WACC	6.18%
		total	6.79%
2.2	Modelling of floating PV systems	PR	0.328% to 0.654%
		WACC	6.18%
		total	6.79%
2.3	Modelling of small PV systems, including building attached PV (BAPV)	PR	0.328% to 0.654%
		WACC	6.18%
		total	6.79%
2.4	Modelling of building integrated PV (BIPV) systems, any size	PR	0.328% to 0.654%
		WACC	6.18%
		total	6.79%
2.5	Modelling of soiling	PR	0% to 0.288%
		WACC	1.56%
		total	1.84%
2.6	Modelling of snow	PR	0% to 1.647%
		WACC	1.56%
		total	3.18%
2.7	Modelling of degradation	WACC	1.56%
2.8	Load profiles generation for self-consumption evaluation	WACC	1.56%
2.9	Modelling of uncertainty and variability and implementation into financial models	WACC	1.56%
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions	WACC	1.56%
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments	WACC	1.56%

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.1.2 Impact of WP3 innovations on LCoE

It is indicated that LCoE is influenced based on higher PR and lower WACC as the result of improved maintenance and better observations and predictability of the system status, in some cases reduced OPEX may have positive impact on the system LCoE. The impact of innovations is calculated based on the PR increase assessed in paragraph 6.1 and the assumed WACC reduction. For illustrative reasons the LCoE calculations for WACC recline contribution are made for 0.5% decline from 10% WACC to 9.5% WACC for all applicable WP3 innovations.

WACC reduction by 0.5% from 10% to 9.5% could result in 3.11% reduction LCoE. For some of the innovations LCoE reductions related to PR and OPEX were identified and presented below. OPEX reduction potential was identified for ‘Failure detection and diagnosis methods for large PV plants’ (3.10) in section 4.5.1 of D8.4. it is stated that developed FDD tool are able to get the main parameters of the IV curve with similar reliability to IV curve tracer measurements (<2% error). Thus, it is assumed that the cost of these inspection technique can be reduced in a 90%. Considering an OPEX of 10 k€/MWp per year, the cost of IV curve inspection is around 10 k€/MWp and that normally it is carried out on a 10% of the PV plant every year, we can estimate a 9% in OPEX reduction thanks to this innovation.

	Innovation name	Contributor	LCoE reduction
3.5	Specific data analytics for soiling	PR	4.80%
		WACC	3.11%
		total	7.8%
3.10	Failure detection and diagnosis methods for large PV plants	PR	1.60%
		WACC	3.11%
		OPEX	2.3%
		total	6.9%
3.13 3.14	PV inverter digital twin and Predictive diagnosis of inverter temperature anomalies	PR	0.40%
		WACC	3.11%
		total	3.5%
3.16	BIPV digital twin	PR	5.30%
		WACC	3.11%
		total	8.2%

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.1.3 Impact of WP4 innovations on LCoE

Similarly to WP3 innovations, the WP4 innovations contribute to PR increase, and reduction of WACC and OPEX. Expected PR increase is due to proactive maintenance and avoided faults of the system and its elements underperformance. Better monitoring contributes to better predictability of the system and reduced uncertainty, which should lead to reduced WACC. Better automatization of monitoring and predictability of fault will also reduce to lower OPEX due to reduced labour costs.

For illustrative reasons the LCoE calculations for WACC recline contribution are made for 0.5% decline from 10% WACC to 9.5% WACC for all applicable WP3 innovations.

7.1.3.1 Measured impact

	Innovation name	Contributor	LCoE reduction
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	PR	0.200%
		WACC	3.11%

		total	3.30%
4.4	New procedures for PV inverters field testing	PR	0.200%
		WACC	3.11%
		total	3.30%
4.6	Procedure for measuring MPPT efficiency in the field	PR	0.020%
		WACC	3.11%
		total	3.13%
4.7	Operating conditions measuring kit	PR	0.020%
		WACC	3.11%
		total	3.13%
4.8	Soiling measurement kit	PR	0.794%
		WACC	3.11%
		total	3.88%
4.13	Procedure for measuring ageing rates in PV modules in the field	PR	0.050%
		WACC	3.11%
		total	3.16%
4.11	Capacitive I-V tracer at 1,500V	PR	0.080%
		WACC	3.11%
		total	3.19%
4.12	Batteries field testing	PR	0.050%
		WACC	3.11%
		total	3.16%
4.14	I-V curve of bifacial PV modules in the field	PR	0.150%
		WACC	3.11%
		total	3.26%

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.1.4 Impact of WP5 innovations on LCoE

None of the owners involved in WP5 envisions an impact from its innovations on the LCoE.

7.1.5 Impact of WP6 innovations on LCoE

LCoE was found not applicable for innovations except for Further integration G2V into self-consumption optimisation software. Neither of the innovations except further integration of G2V into self-consumption optimisation on MV/LV grid does not have an impact on LCoE according to all innovation owners.

7.1.5.1 Measured impact

	Innovation name	LCoE reduction
6.4	Further integration G2V into self-consumption optimisation software	21% - 53%
6.6	Real-time control and market system enabling the participation in ancillary services by a pool of PV pants (without storage)	5.75 €/MWh (no reduction)

Integration of the G2V into self-consumption allows for increase of the self-consumption of generated PV electricity and reduction of curtailment or selling to grid with reduced price. That contributes to higher utilisation of the electricity form PV system and consequently lower LCoE (assuming the constant system cost).

Assumptions: an electrical car driving 10,000 kms per year at 15kWh per 100 kms (4.5 kWh/day on average – 1500 kWh/year). Electricity price is 20cts/hour (off-peak price) – charging the car only on off-peak hours at home would cost 300 /year.

Parner took 2 scenarios to simulate the impact of its smart charging station on 185 PV systems (2.5 to 3.5kWp: ~3500 kWh/year):

- Charge at night during the week and during the day on weekends: increase of the self-consumption from 51% to 60% - 315kWh saved = 63 €/year, LCoE is 0.158 €/kWh (21% cheaper)

Charge during the day: increase of the self-consumption from 51% to 74% - 805kWh saved = 161 €/year, LCoE is 0.093 €/kWh (53% cheaper)

As initially presented in D6.6 and later demonstrated in D8.11, it is possible to calculate the LCoE for one of the large PV installations used to demonstrate the German redispatch schema. The LCoE can be calculated by first taking the net present value of the total cost of building and operating the power generating asset. This number is then divided by the total electricity generation over its lifetime. Given the NVP calculation being 34,500,000 € with a 7.3 % interest rate after tax over 10 years period, one can conclude an LCoE over a period of 10 years to be 5.75 €/MWh. This number cannot be calculated a reduction given that the calculation is made for a new installation where the lifetime starts at 0.

7.2 Profile factor

The PF describes how the hour-to-hour solar PV production profile compares to the price profile of the wholesale electricity market. In this case, the wholesale electricity market price is the same as that in the merchant power purchase agreement (PPA). The PF is calculated as the ratio of the average wholesale electricity price weighted by the produced electricity from PV in each time step to the average wholesale electricity price. Only actual power production data, not forecasted ones, are used in the calculation while the day-ahead wholesale electricity price is usually the one used. This metric is useful for independent power producers, even if their PPA is under a fixed price. That is because they would have to buy the demand not met by solar PV production on the wholesale market. The PF can be complemented by the imbalance factor, which is discussed in detail in **“D1.1 KPIs on state-of-the-art PV reliability, performance, profitability and grid integration”** [1]. It is usually calculated on a yearly basis to account for seasonal fluctuations in production and prices. Equation (12) shows how the PF is calculated.

$$PF = \frac{\sum_n Q_n \cdot P_n}{\sum_n Q_n} / \frac{\sum_n P_n}{N} \tag{12}$$

Where:

- PF: profile factor [-]
- n: hour n of a year, varying between 1 and N
- N: total number of hours in a year, i.e. 8760
- Q_n: volume of produced PV electricity in hour n [kWh]
- P_n: wholesale electricity market price in hour n [€/kWh]

A few of the SERENDI-PV project innovations have a potential impact on the PF according to expert opinion. These were outlined in the table **¡Error! No se encuentra el origen de la referencia.**. A more detailed explanation of these impacts follows below.

7.2.1 Impact of WP2 innovations on PF

Owners of innovations, envision these innovations to be non-influential in case of the PF.

7.2.2 Impact of WP3 innovations on PF

All the innovations under WP3 have not been found as having an impact on PF.

7.2.3 Impact of WP4 innovations on PF

It is recognized that none of the innovations under WP4 impact on the PF.

7.2.4 Impact of WP5 innovations on PF

PF was calculated for 'Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)' (5.1) and 'Forecasting applied to residential PV systems' (5.6). For other innovations the PF was not calculated due to short period of available measurements. The innovations do not contribute to actual increase of PF, but contribute to its better forecasting.

The available results were demonstrated at the site in southern Germany, available data covers period from 1st of August 2022 to 31st July 2023. The PF was calculated for the forecast based on newly developed method, forecast based on previously existing methods and real measured PV output as a reference. The hourly day-ahead prices for 2022-2023 taken from German federal grid agency cite www.smard.de [16].

The results how interesting effects, due to strong influence of variable market electricity prices improvement of forecasting in standard mathematical terms (lower RMSE, MAE etc.) does not necessary lead to more reliable PF calculations.

7.2.4.1 Measured impact

	Innovation name	PF value	PF old method	PF real
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)	90.18%	89.67%	88.90%
5.6	Forecasting applied to residential PV systems	94.98%	94.67%	97.50%

For innovation 5.1 the forecasting leads to overestimation of PF, however the results strongly depend on the day-ahead prices profiles. In 2022 the electricity prices in Germany were volatile due to war induced energy crisis. When 2023-2024 prices are applied, the PF for both innovations show reasonable value below the measured PF.

For both innovations and all years, new forecasting methods result in increase of PF compared to value calculated using the previously existing forecast methods.

7.2.5 Impact of WP6 innovations on PF

The only innovation that has been found applicable is Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage). The other innovations from this WP are not primarily found to have an effect on PF.

7.2.5.1 Measured impact

	Innovation name	PF value	Origin deliverable	Ref

6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)	N/A		

Unfortunately, the Profile Factor KPI has not been calculated by partners given that the innovation and related demonstrations (redispatch in Germany and aFRR in the Netherlands) are not affected by this KPI.

7.3 Weighted average cost of capital

The discount rate, mentioned earlier, is the after-tax weighted average cost of capital. The WACC reflects the level of risk associated with investing in a certain project at the time of investment and is usually assumed to remain constant over the lifetime of the project for simplification reasons. Several factors can affect the WACC, of which some are endogenous to the project type and some are exogenous depending on where the investment is made. Endogenous factors include the maturity level and track record of the technology used and the system components. Exogenous factors include market risks, regulatory risks, and resource risks. There is a nominal WACC and a real WACC, which are calculated as shown below:

$$WACC_{nom} = \frac{D}{D+E}(1-T_c)\cdot r_D + \frac{E}{D+E}\cdot r_E \tag{13}$$

$$WACC_{real} = \frac{1+WACC_{nom}}{1+Inflation} - 1 \tag{14}$$

Where:

- $WACC_{nom}$: nominal weighted average cost of capital [- or %]
- D: the used amount of debt [€]
- E: the used amount of equity [€]
- r_D: cost of debt, i.e. effective interest rate paid on debts [-]
- r_E: levered cost of equity, i.e. return rate required for an investment [-]
- T_c: average corporate tax rate [-]
- $WACC_{real}$: real weighted average cost of capital [- or %]
- Inflation: estimated average annual inflation [-]

According to expert opinion, several of the innovations of SERENDI-PV have a potential impact on the WACC. From the proposal phase of the SERENDI-PV project, the working theory is that a reduction of the WACC could be conveyed to the financial sector from the PV industry by providing better energy yield assessments, better quality control as well as better component and system reliability. Better assessment will result in lower uncertainty of the project operation during lifetime and consequently lower risks which should contribute to reduction of the WACC. The influential ones are discussed more below.

7.3.1 Impact of WP2-6 innovations on WACC

One of the objectives of accomplishing advanced modelling, data analytics, or quality control procedures is to reduce the uncertainty related to the PV plant performance progressively and, consequently, the risks associated to PV investment [17], [18], [19]. Uncertainty in the initial energy yield forecasting determines the financial backing of the project [19], [20], [21]. When defining the initial estimates of the project, a simulation is carried out, resulting in the expected P_{50} value. Then, each uncertainty source affecting the simulation is treated as a Gaussian random variable and combined to calculate the overall technical uncertainty in the estimation, which, in turn, can be expressed as the combination of three different uncertainty groups:

$$\sigma_{Ov,F} = \sqrt{{\sigma_{SR}}^2 + {\sigma_{SIM}}^2 + {\sigma_{PER}}^2}$$

where σ_{SR}, σ_{SIM} and σ_{PER} are, respectively, the uncertainties in the broadband horizontal solar radiation, the simulation process and the PV system performance characteristics. Table 7.2 presents the components of each uncertainty group and typical values for both the first year of operation and an overall period of 30 years. It is worth remembering that the energy yield forecasting is performed before the project is started, when the only available information are the database solar radiation and the manufacturer datasheets.

Table 7.2: Main sources of uncertainty in the energy yield forecasting of a PV project. The estimation is carried out at the beginning of the project, when the only information available are the database solar radiation and the manufacturer datasheets.

Uncertainty source	First year uncertainty(%)	30-year uncertainty(%)
Solar radiation		
Solar radiation database, σ_{DB}	4.5 [1]	1.2
Variation from year to year, σ_{AV}	5.0	0.9 [2]
Long-term trend, σ_{LT}	N.A.	1.5 [3]
Simulation		
Dust, σ_{DU}	2.0 [4]	
Operating conditions, σ_{OC}	2.2 (static) [5] 2.7 (tracking)	
Power response, σ_{PR}	1.0	
System performance		
PV system initial characteristics, σ_{SC}	3.5 [6]	
Ageing, σ_{AG}	N.A.	3.0 [7]

[1] The uncertainty declared by the solar radiation databases is varied. In this text, the PVGIS uncertainty has been considered as an intermediate value. This assumption is in line with what presented in other works [21].

[2] Radiation variation from year to year is strongly dependent on orography and climatic region [21], [22]. As a general value we have considered a 5% annual uncertainty.

[3] Long-term radiation variations are time and site dependent. In the last decade, a general brightening of the sky has occurred, and predictions for the future evolution go in the same direction. For this study, a 30 years mean of 1.5% has been considered, according to some recent publications [23], [24].

[4] Dust affection is dependent on the location and the surroundings composition. Considering an State of Art maintained PV plant, 2% affection is used as a general case and 7% affection in dry and desert environments. 2% uncertainty is considered in both cases.

[5] This parameter considers the modelling of G^{ef} (2% for static structures and 2.5% for one-axis tracking ones) and T_C (1.0%).

[6] It encompasses PV array rating (2%), PV module temperature coefficients (1%), PV modules *LID* (2%), inverter (1%), ancillary consumption (1%), transformer (1%) and other field-related issues (2%).

[7] Ageing depends on the location as it is a function of the *UV* radiation received by the PV modules. Typical values range from 0.3% to 0.7% of annual degradation with a 0.2% standard deviation.

In particular, the uncertainty sources are:

- Solar radiation database, σ_{DB}: despite satellite models adjust their databases according to in-field measurements they present both a mean bias error and a standard deviation around it depending on the particular location. In general, uncertainty is lower for regular orographies and regions with a dense net of on-ground meteorological stations, and higher for remote areas or regions with large altitude gradients or close to the sea.

- Variation from year to year, u_{AV}: this distribution is, by definition, centred on the mean value given by the solar radiation database and, therefore, it entails no systematic error. The standard deviation is calculated by considering the range between the extreme yearly broadband irradiation values observed over a period of 15 years as the 95% confidence interval of the distribution.

- Long-term, u_{LT}: solar radiation is subject to decadal cycles and other long-term trends, due to atmospheric composition (SO_X and NO_X emissions, volcanos, etc.). Available literature shows that the magnitude of these trends strongly varies depending on the location and the temporal period considered [23], [24].

  Dust, u_{DU}: the simulation considers a mean dust cover as a part of the allowable losses package, leaving the standard deviation component as uncertainty.

- Operating conditions estimation, σ_{OC}: it includes the pass from $G(0)$ to G^{ef} and from T_A to T_C. The uncertainty calculation derives from the comparison of estimated values to measured values, recorded at several well-maintained PV installations.

- PV modules power response, σ_{PR}: as already mentioned, SISIFO relies on certain models for considering the PV array efficiency dependence on irradiance and operating temperature, and by considering the influence of the relative load on the efficiency of inverters and transformers. These models include adjusting parameters which are fitted to the information provided by equipment manufacturers. Uncertainty derives from possible differences between the real performance and the performance described by this information, namely as regards the efficiency of PV arrays.

- PV system characteristics, σ_{SC}: this parameter encompasses the uncertainties related to the difference between the nominal and the real STC values derived from manufacturing tolerance, initial LID of the PV modules, power variation coefficients with temperature and irradiance, differences between the real and theoretical efficiency in inverters and transformers, voltage drop at the wiring, characteristics mismatching, etc.

- Ageing, σ_{AG}: according to available literature, the degradation margin observed for crystalline silicon varies from between 0.4% and 0.8% of power loss per year. This way, degradation at the end of N years can be estimated by a mean value decreasing over time, at a 0.6% yearly ratio, and a standard deviation increasing over time, at a 0.1% yearly ratio. For a period of 20 years, that leads to an overall uncertainty of 2%.

Table 7.3 shows the improvement in the uncertainty sources derived from the application of WP4 innovations.

Table 7.3: Main uncertainty improvements in the energy yield forecasting derived from the application of WP4 innovations.

Uncertainty source	First year uncertainty(%)	30-year uncertainty(%)

Solar radiation		
Solar radiation database, σ_{DB}	2.2	0.9
Variation from year to year, σ_{AV}	5.0	0.9
Long-term trend, σ_{LT}	N.A.	1.5
Simulation		
Dust, σ_{DU}	0.5	
Operating conditions, σ_{OC}	1.0	
Power response, σ_{PR}	0.5	
System performance		
PV system initial characteristics, σ_{SC}	1.0	
Ageing, σ_{AG}	N.A.	1.0

Table 7.4 presents the results of the overall uncertainty associated to the yield estimation of a PV project, depending on the type of structure. According to these data, uncertainty is 8.2% for the first year of operation and 6.0% considering a 30-years period, when simulating static structures. In one-axis tracking systems, these results are, respectively, 8.4% and 6.2%. The application of advanced quality assurance procedures coming given by WP4 innovations during the design, procurement and commissioning phases reduces those values to 5.8% and 2.9% respectively, more than 50% for both static and tracking systems. This result leads to an increase in the $E_{P_{90}}$ and $E_{P_{95}}$ values (which are the values used for the project financing) of, respectively, 4.6% and 9.0%.

Table 7.4: Uncertainty values according to traditional energy yield forecasting and including WP4 innovations, for static and tracking structures and for the first year of operation and a 30-year period.

Overall uncertainty in the energy yield estimation (%)						
Period	Static systems			One-axis tracking systems		
	Traditional	WP4 innovations	Improvement	Traditional	WP4 innovations	Improvement
First year	8.2	5.8	-29%	8.4	5.8	-31%
20-year	6.0	2.9	-52%	6.2	2.9	-53%

Figure 7.1 shows the evolution of the yield estimation probability function once these advanced procedures have been implemented.

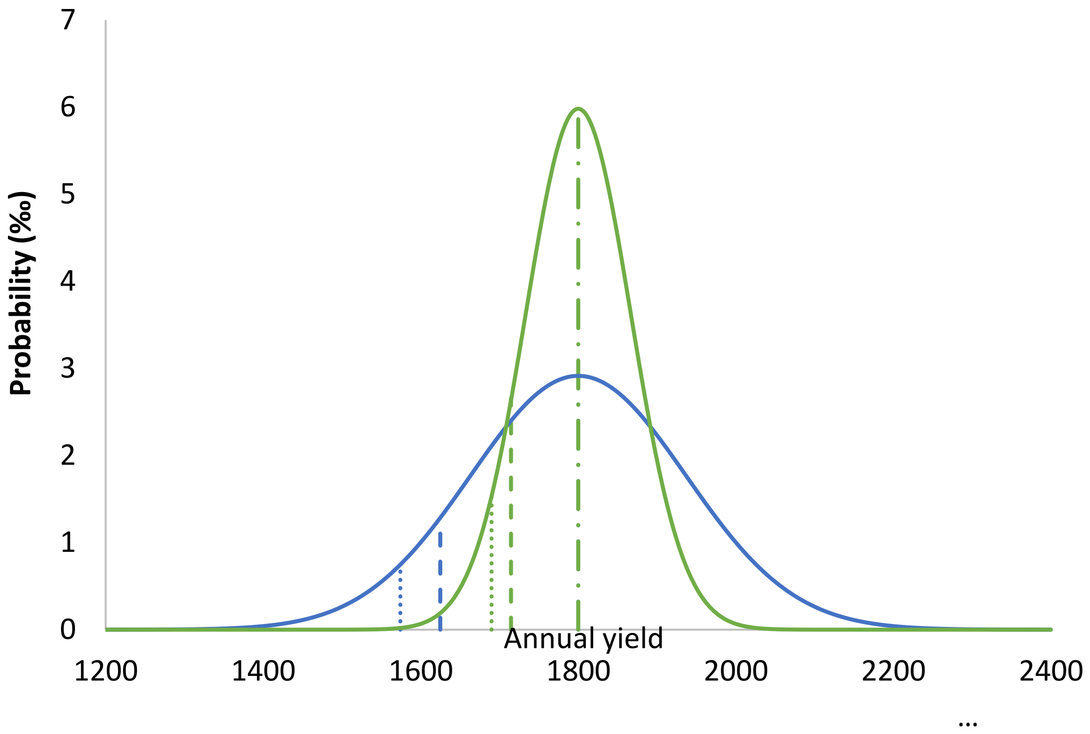

Figure 7.1: Evolution of the energy estimation probability function after the application of advanced quality assurance procedures.

Though the dependence of the WACC level on the uncertainty is well studied, the direct dependency does not exist as the WACC depends on multitude of non-technical aspects and even for same technical conditions substantially varies over time and country to country.

7.3.2 Impact of WP2 innovations on WACC

WP2 innovations represent the modelling methods aiming for better prediction of the system operation and prediction of certain factors affecting the system performance. More accurate modelling will allow for better design of the system and will contribute to lower uncertainty of the system output over lifetime of the project, reducing the risks and increasing bankability of the project. As it was described earlier lower uncertainty and lower risks at the project planning stage will contribute to lower risk perception and lower WACC for the project. The improvement of overall system modelling accuracy may have substantial impact on the project and can contribute to about 1% reduction of WACC, improvement of certain aspects will naturally have more limited impact, but it may reach 0.25%. However, in real conditions WACC will strongly depend on many other non-technical parameters.

7.3.2.1 Measured impact

	Innovation name	WACC reduction
2.1	Modelling of bifacial PV systems	up to 1%
2.2	Modelling of floating PV systems	up to 1%
2.3	Modelling of small PV systems, including building attached PV (BAPV)	up to 1%
2.4	Modelling of building integrated PV (BIPV) systems, any size	up to 1%
2.5	Modelling of soiling	up to 0.25%

2.6	Modelling of snow	up to 0.25%
2.7	Modelling of degradation	up to 0.25%
2.8	Load profiles generation for self-consumption evaluation	up to 0.25%
2.9	Modelling of uncertainty and variability and implementation into financial models	up to 0.25%
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions	up to 0.25%
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments	up to 0.25%

7.3.3 Impact of WP3 innovations on WACC

WP3 innovations represent the data analytics methods aiming for better analysis of the system operation parameters and identification of the anomalies in its operation and detection of arising faults. This data analysis and fault propagation allows for proactive maintenance and leads to more stable operation of the system and more reliable prediction of its output over lifetime of the project. As it was described earlier lower uncertainty and lower risks at the project planning stage will contribute to lower risk perception and lower WACC for the project. The improvement of the data analysis will have substantial impact on the project and can contribute to about 0.5% reduction of WACC, however in real conditions WACC will strongly depend on many other non-technical parameters.

7.3.3.1 Measured impact

	Innovation name	WACC value
3.1	Specific data analytics for bifacial PV systems	0.5%
3.2	Specific data analytics for floating PV systems	0.5%
3.3	Specific data analytics for small PV systems, including BAPV	0.5%
3.4	Specific data analytics for BIPV systems, any size	0.5%
3.5	Specific data analytics for soiling	0.5%
3.6	Specific data analytics for vegetation	0.5%
3.7	Specific data analytics for snow	0.5%
3.8	Specific data analytics for degradation	0.5%
3.9	IR imaging data analytics	0.5%
3.10	Failure detection and diagnosis methods	0.5%
3.11	Fault detection/diagnosis toolbox for small PV	0.5%
3.12	PV inverter efficiency characterisation	0.5%
3.13	Predictive diagnosis of inverter temperature anomalies	0.5%
3.14	PV inverter digital twin	0.5%
3.15	PV battery digital twin	0.5%
3.16	BIPV digital twin	0.5%

7.3.4 Impact of WP4 innovations on WACC

Similarly to WP3, innovations developed in WP4 contribute to better analysis of the system operation parameters and identification of the anomalies in its operation and detection of arising faults. This fault propagation allows for proactive maintenance and leads to more stable operation of the system and more reliable prediction of its output over lifetime of the project. As it was described earlier lower uncertainty and lower risks at the project planning stage will contribute to lower risk perception and lower WACC for the project. The improvement of the data analysis will have substantial impact on the project and can contribute to about 0.5% reduction of WACC, however in real conditions WACC will strongly depend on many other non-technical parameters.

7.3.4.1 Measured impact

	Innovation name	WACC value
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	0.5%
4.4	New procedures for PV inverters field testing	0.5%
4.6	Procedure for measuring MPPT efficiency in the field	0.5%
4.8	Soiling measurement kit	0.5%
4.13	Procedure for measuring ageing rates in PV modules in the field	0.5%
4.11	Capacitive I-V tracer at 1,500V	0.5%
4.12	Batteries field testing	0.5%
4.14	I-V curve of bifacial PV modules in the field	0.5%

7.3.5 Impact of WP5-6 innovations on WACC

None of the innovations developed under working packages 5, and 6 are expected by any of the owners and project partners to be influential when it comes to the WACC.

7.4 Net present value

An annual income and loss statement includes all acquired positive and incurred negative cash flows during the year in question. These are then summarised to calculate a net profit or net loss for that year. This is also called the annual free cash flow. All the annual free cash flows over the lifetime of a project can then be discounted to a base year and summed up to calculate the net present value of the project. The annual free cash flow for NPV, and subsequently (M)IRR excludes cost of capital and in particular cost for interests and financing costs, as this is captured in the discount rate [25]. The NPV of a project is highly dependent on its size and financing circumstances. It is not sufficient on its own to reflect the profitability of a project or to compare it with other projects. Thus, it is complemented by the modified internal rate of return, described in the following sub-section, or normalised with respect to the nominal installed DC capacity of a solar PV project. The formula used to calculate the NPV is shown below:

$$NPV = \sum_{i=0}^{N} \frac{Free\ Cash\ Flow_i}{(1+d)^i} = -I + \sum_{i=1}^{N} \frac{Free\ Cash\ Flow_i}{(1+d)^i} \tag{15}$$

Where:

- NPV: net present value for a theoretical system lifetime of N years [€]
- N: theoretical system lifetime [years]
- Free Cash Flow$_i$: free cash flow in year i [€]
- d: discount rate [%]
- I: initial investment in year 0 [€]

The table **¡Error! No se encuentra el origen de la referencia.** summarised partners´ opinions on which SERENDI-PV innovations have a potential impact on the NPV, and which do not. The impactful ones are also discussed in more detail below.

7.4.1 Impact of WP2 innovations on NPV

Similarly to LCoE, the NPV will be affected by WP2 innovations in two different ways. On one hand, improved modelling of the PV system may allow for better consideration of the environment impact and design adaptation to reduce environment related losses as discussed in paragraph 6.1. On another hand, improved modelling methods will contribute to reduced uncertainty at the project preparation stage, and better bankability of the project, lower risks and consequently lower WACC compared to projects with higher uncertainty.

7.4.1.1 Measured impact

	Innovation name	Contributor	NPV increase
2.1	Modelling of bifacial PV systems	PR	0.329% to 0.658%
		WACC	31.5%
		total	31.7%
2.2	Modelling of floating PV systems	PR	0.329% to 0.658%
		WACC	31.5%
		total	31.7%
2.3	Modelling of small PV systems, including building attached PV (BAPV)	PR	0.329% to 0.658%
		WACC	31.5%
		total	31.7%
2.4	Modelling of building integrated PV (BIPV) systems, any size	PR	0.329% to 0.658%
		WACC	31.5%
		total	31.7%
2.5	Modelling of soiling	PR	0% to 0.289%
		WACC	7.1%
		total	7.2%
2.6	Modelling of snow	PR	0% to 1.674%
		WACC	7.1%
		total	7.1%
2.7	Modelling of degradation	WACC	7.1%
2.8	Load profiles generation for self-consumption evaluation	WACC	7.1%
2.9	Modelling of uncertainty and variability and implementation into financial models	WACC	7.1%
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions	WACC	7.1%
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments	WACC	7.1%

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.4.2 Impact of WP3 innovations on NPV

NPV impact of WP3 innovations can be affected by WACC reduction and PR increase. WACC reduction by 0.5% from 10% to 9.5% alone could result in 14.6% increase of NPV. For some of the innovations NPV increase related to PR was identified and presented below.

	Innovation name	Contributor	NPV increase
3.5	Specific data analytics for soiling	PR	5.0%
		WACC	14.6%
		total	15.4%
3.10	Failure detection and diagnosis methods for large PV plants	PR	1.6%
		WACC	14.6%
		total	14.9%
3.13 3.14	PV inverter digital twin and Predictive diagnosis of inverter temperature anomalies	PR	0.425%
		WACC	14.6%
		total	14.7%
3.16	BIPV digital twin	PR	5.625%
		WACC	14.6%
		total	15.5%

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.4.3 Impact of WP4 innovations on NPV

Similarly to case of LCoE, the WP4 innovations contribute to increase of NPV via PR increase, and reduction of WACC and OPEX.

For illustrative reasons the LCoE calculations for WACC recline contribution are made for 0.5% decline from 10% WACC to 9.5% WACC for all applicable WP3 innovations.

7.4.3.1 Measured impact

	Innovation name	Contributor	NPV increase
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	PR	0.18%
		WACC	14.6%
		total	14.7%
4.4	New procedures for PV inverters field testing	PR	0.18%
		WACC	14.6%
		total	14.7%
4.6	Procedure for measuring MPPT efficiency in the field	PR	0.02%
		WACC	14.6%
		total	14.6%
4.7	Operating conditions measuring kit	PR	0.02%
		WACC	14.6%
		total	14.6%
4.8	Soiling measurement kit	PR	Average: 0.8% Worst case: 4%
		WACC	14.6%
		total	14.8%
4.13	Procedure for measuring ageing rates in PV modules in the field	PR	0.05%
		WACC	14.6%

		total	14.7%
4.11	Capacitive I-V tracer at 1,500V	PR	0.08%-0.09%
		WACC	14.6%
		total	14.7%
4.12	Batteries field testing	PR	0.05%
		WACC	14.6%
		total	14.7%
4.14	I-V curve of bifacial PV modules in the field	PR	0.15%
		WACC	14.6%
		total	14.7%

The calculations of LCoE are made based on assumptions that reference project 75% of budget comes from CAPEX and 25% from OPEX, WACC is set to 10% given a 30-year lifetime.

7.4.4 Impact of WP5 innovations on NPV

The owners and project partners do not expect the innovations from WP5 to impact the NPV. This is because the NPV is not based on forecasted data. The only exception would be if the implementation costs of such innovations are considered as part of the PV electricity generation system, according to TEC. In this case, the operation expenditures would increase which lowers the NPV.

7.4.5 Impact of WP6 innovations on NPV

For WP6 innovations PF was found not applicable as KPI except for innovations 6.1 “Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)” and 6.6 “Predictive EMS for PV storage self-consumption”.

7.4.5.1 Measured impact

As provided the background for in D6.6 and later demonstrated in D8.11, it is possible to calculate the Net Present Value for one of the large PV installations used to demonstrate the German redispatch schema. With the values for the installed capacity, annual electricity production, and expected electricity production in 10 year and assuming a discount rate of 7,3% one can insert these values into the formula. This shows us that the 605 MWp installation used for demonstration purposes is discounted to today’s value worth 34.5 million € throughout its lifetime.

Regarding innovation 6.6 “Predictive EMS for PV storage self-consumption”, savings in the electricity bill will be measured when operating with the new predictive EMS and they will be compared with the savings achieved with a conventional EMS of PV storage systems, based on instantaneous measurements and maximizing self-consumption ratio. These savings can be easily calculated from the monitored PV generation and building consumption profiles by simulating the conventional EMS. As a result, NPV of the storage system can be computed for both energy management strategies and the impact of the innovation evaluated.

	Innovation name	NPV value	Origin deliverable	Ref
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)	34,500,000 €*	D8.11 (section 2.1.3)	
6.6	Predictive EMS for PV storage self-consumption	13.3€/kWh**	D8.11 (section 17.3)	

* The NPV with 7.3 % interest rate after tax over 10 years period.

**This means make BTM storage profitable within its lifetime in comparison to conventional EMS with NPV of -49.5€/kWh.

7.5 (Modified) Internal rate of return

The IRR is the discount rate at which the NPV would be exactly equal to zero. The MIRR is a variation in which financing and reinvestment rates are differentiated to better mirror reality. The MIRR also has different versions depending on the calculation used. One is the project MIRR, which is calculated for the solar PV asset and disregards the financing conditions. Another is the equity or levered MIRR, where the financing conditions are considered, which is important for equity investors. Both values are usually calculated as they provide important information for different types of stakeholders. In all cases, the (M)IRR should be at least equal to the WACC of the project in question. The free cash flow considered for NPV and (M)IRR calculations exclude cost of capital and in particular cost for interests and financing costs, as this is captured in the discount rate [25].

7.5.1 Impact of WP2-6 innovations on (M)IRR

The (M)IRR could be improved via reduction of negative cash flows (costs of the system) and via increase of positive cash flow (revenue). The WP2-6 innovations do not show impact on the system costs, none of the innovations have claimed reduction of CAPEX, for some WP3 and WP4 innovations OPEX reduction is expected, but not quantified. Positive cash flow depends on the system output and electricity prices profiles. The innovations do not have direct impact on the electricity prices, however some of innovations have limited impact on PR improvement.

However, the expected PR improvement is not significant to be reflected in sensible impact on (M)IRR, considering the PV systems technical lifetime. Impact of the WP2-6 on (M)IRR was found to be negligible.

8 Grid indicators for WP6

The increasing proliferation of PV systems in the European electricity grids will challenge the grid operators to maintain and ensure a stable and safe operation of the electricity grid. The impact and consequences for the grid, such as congestion problems, frequency and power quality issues have to be adequately managed via introduction of new standards, equipment and innovative methods of control. D1.1 [1] selected four grid service indicators that better reflect technological capability of a PV system to provide grid services. These are Possibility to control power output (PCPO), Obligation to participate in system services with PV (OPSS), Possibility to participate in market based system services with PV (PPMS) and Availability of live data (ALD). The Grid service indicators levels are presented in Figure 8.1. For more details on the grid service indicators, the **"D1.1 KPIs on state of the art PV reliability, performance, profitability and grid integration"** [1] can be consulted.

Table 8.1: Grid service indicators quantitatively described and expressed as levels

Grid indicators	Level 1	Level 2	Level 3	Level 4
Possibility to control power output (PCPO)	No	Yes, remote control with reaction time > = 3''	Yes, local control or remote control with reaction time between 3'' - 1''	Yes, remote control with reaction time < = 1''
Obligation to participate in system services with PV (OPSS)	No	Yes, with restriction of market based system services	Yes	
Possibility to participate in market based system services with PV (PPMS)	No	Yes, PV is not treated non-discriminatory (negatively)	Yes, PV is treated non-discriminatory or treated beneficial compared to other technologies	
Availability live data (ALD)	No	Yes, with temporal resolution about 60'', with delay between 60''-15''	Yes, with temporal resolution about 15'', with delay between 15''-1''	Yes, with temporal resolution < = 1'', with delay < =1''

Table 8.2: Summary of the impact of SERENDI-PV innovations on profitability KPIs

ID	Innovation	PCPO	OPSS	PPMS	ALD
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)	X	X	X	X
6.2	Automated data model integration framework for PV integration and communication in DSO data systems	X			X
6.3	Digital twin of the grid with high PV contribution	X			X
6.4	Further integration G2V into self-consumption optimisation software	X			X
6.5	Implementation of IEC61850 for data communication on MV/LV grid	X			X
6.6	Predictive control-based EMS for PV storage self-consumption optimisation	X			

ID	Innovation	PCPO	OPSS	PPMS	ALD
6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)	X	X		X
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems	X			X
6.9	Operation of PV ensuring active power reserve available to provide ancillary services			X	

8.1 Possibility to control power output

A basic requirement to provide grid services with solar PV is to have a controllable system. This could be a local control mechanism based on an on-site optimization or a local grid optimization - e.g., based on the voltage of the PCC (Point of Common Coupling) - or being able to be controlled remotely. In order to be able to provide advanced system services, remote controllability is often a must, since most of them are centrally controlled.

8.1.1 Impact of Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)

How the innovation affects the indicator:

It is of utmost importance to have the possibility to control the power output to be able to provide a real time control system to offer ancillary services. For all grid related services there exists strict regulation when it comes to reaction times and how much volume that can be offered to the TSO is linked to the ramp rate of the asset.

The formula/method used to estimate the indicator value:

The possibility to control the power output can be calculated as a percentage of the gradient. For the used demonstration site, a larger PV site in Germany, the minimum acceptable ramp-down gradient = 0.5%

$$Gradient = 100 \times \frac{Available\ power\ in\ production}{Time\ to\ reach\ zero\ power} = 0.55\ \%$$

Secondly, to support the innovation it was attempted to demonstrate aFRR provision with a PV plant in the Netherlands. When doing so it was noticed that specifically the controlling of the power output was lacking. Rather than smoothly adjusting power output, the controller abruptly shut down the inverters, causing a sudden, steep drop in production. This behavior suggests that the asset struggles to maintain continuous production during control commands, which is crucial for delivering aFRR services. This means that the aFRR demo was not successful exactly because this indicator could not be fulfilled, which also highlights the importance of the possibility to control power output.

8.1.2 Impact of Automated data model integration framework for PV integration and communication in DSO data systems

How the innovation affects the indicator: The innovation will allow the advanced utilization of standardized data models and communication protocols to improve automation mechanisms interoperability, which further enables the standardized control of multiple parameters (depending on the data model size, at least 1 parameter for active feed-in power). Regarding the Possibility to control power output (PCPO), the maximal reaction time to these grid commands is in the range of **level 4 in the laboratory and level 3 in the field demonstration**.

The formula/method used to estimate the indicator value: In terms of providing grid-supporting service, remote controllability is one advantage of utilizing the standard SunSpec and IEC 61850 data models and communication protocols. In this specific case, a telecommunication interface consisting of two segments:

- segment 1: SunSpec between the PV inverter and the IEC 61850 server
- segment 2: IEC 61850 MMS between the IEC 61850 server and the IEC 61850 client

it is not easy to calculate the total reaction of a control command from being sent by the control unit till being executed physically by the inverter, but the IEC 61850 server will always send a response back to the server after receiving a control command. Therefore, the innovation in ER6_2 is validated by measuring the following reaction of the IEC 61850 server:

$$Reaction\ time = time\ of\ client\ recieving\ a\ response\ -\ time\ of\ client\ sending\ a\ control$$

This KPI measures the time difference from the moment of sending a control command from the IEC 61850 client, till receiving a response TCP packet sent by the IEC 61850 server with the control status flag “success”. For this ER, direct measurement or calculation of the power change on the inverter side is not possible, but the power change can be seen and validated in the next IEC 61850 MMS packet.

The measured time from the moment of sending a control command from the IEC 61850 client, till receiving a response TCP packet sent by the IEC 61850 server with the control status flag “success”. For this ER, direct measurement or calculation of the power change on the inverter side is not possible, but the power change can be seen and validated in the next IEC 61850 MMS packet.

8.1.3 Impact of Digital twin of the grid with high PV contribution

How the innovation affects the indicator: This innovation presents a method for the grid simulation (grid digital twin) that enables the grid state monitoring based on the real-time measured data, PV systems meta data and other available sources of data. In case a grid congestion is observed in the simulation results, the creation of real time congestion measures will result in control signals, which will be sent to the PV inverters in the field, based on the method explained in the previous section.

The reaction time to these grid commands is then based on the reaction time explained in the previous section 8.1.2. However, the additional time required for the exporting the control command from the digital twin environment, which is usually in terms of milli seconds, should be also considered. It should be taken into consideration that the time required for the grid state estimation and for finding a suitable congestion measures (i.e. based on the algorithms described in D6.4), which can be in terms of few seconds to one minute, are not considered in the reaction time for the control command. Similarly to the previous section, the maximal reaction time to these grid commands is in the range of **level 4 in the laboratory and level 3 in the field demonstration**.

8.1.4 Impact of Further integration G2V into self-consumption optimisation software

How the innovation affects the indicator: firmware/hardware lowers the charging station output power within few seconds to avoid that the total consumption of the house exceeds the contracted power of the house.

Our system could also be used to send commands to increase/decrease the charging power of an electrical car with less than 30 seconds from our Cloud. As partner will have its piloting systems in 100s or 1000s of houses, few MWs of power could be potentially controlled.

The formula/method used to estimate the indicator value: At the moment, partner does react to grid commands but partner can measure the time between Cloud commands and the reaction on the local device by seeing the impact on the consumption of the device (the consumption is sent to the Cloud).

8.1.5 Impact of Implementation of IEC 61850 for data communication on MV/LV grid

How the innovation affects the indicator:

In the past, data communication for a variety of IoT devices came with a high variety of standard or non-standardised communication protocols. This led to additional workload in developing adapters for the individual devices operating with different communication protocols in order to establish a communication between those individual devices and overlaying systems. The more different protocols or interfaces involved the longer the communication between different devices last. This is relevant both in the retrieval of data and the resulting control actions sent to local devices based on the evaluation of the retrieved data beforehand. With the introduction of the standard data model of the IEC 61850 the realisation of control actions can be implemented directly. As a matter of the implementation, **PCPO Level 3** for sending and receiving the control action can be achieved. Additionally. **PCPO Level 2** with a reaction time between 30 – 2 seconds can be reached for time until the execution of the control action.

The formula/method used to estimate the indicator value:

To estimate the reaction time, two differentiations are made. On the one hand site the reaction time to send and receive the command is measured, while on the other hand site the reaction time from receiving the control action to actually reaction is measured.

8.1.6 Impact of Service system for aggregating anonymous data for the monitoring and management of distributed generation systems

How the innovation affects the indicator:

While the primary aim of ER6_8 is to ensure the secure and anonymised transmission of data from self-consumption photovoltaic (PV) installations, its impact on PCPO is reflected in its ability to provide real-time access to distributed energy production data. By delivering timely, anonymised, and geographically aggregated data through an IoT-based platform, the innovation enables grid operators to make informed decisions and issue control commands where necessary, even though individual installation control is not the focus.

The architecture of ER6_8 is built to facilitate the scalable aggregation of data, meaning that the platform can support remote control capabilities for broader geographical areas rather than individual installations. This contributes to **PCPO Level 3**, where grid operators can issue commands based on aggregated data, ensuring that output control mechanisms can be applied to entire regions or groups of installations, contributing to grid balancing.

The innovation further enhances PCPO by allowing grid operators to maintain oversight of aggregated power output, enabling smoother interaction with ancillary services and ensuring that power output can be adjusted in response to changing grid conditions. As more distributed energy resources are integrated into the grid, the scalability of the platform ensures that this control mechanism remains effective, even as the number of installations grows.

The formula/method used to estimate the indicator value:

While the ER6_8 innovation does not directly contribute to improving the granularity of the control of power output, it does enable grid operators to achieve PCPO Level 3 by providing secure, real-time, and aggregated data from distributed energy resources, which allows operators to issue control commands based on regional or group-level data.

As a result, we have not defined specific KPIs that directly impact the PCPO metric, since ER6_8 primarily enables control possibilities rather than improving the fine-tuning or responsiveness of power control. The platform ensures that power output control can be implemented in a secure and anonymised manner, but does not introduce specific enhancements to the precision of the control itself.

However, specific KPIs were defined to evaluate the performance and effectiveness of the innovation. These KPIs, which focus on aspects such as data integrity, scalability, and cybersecurity, are detailed in Chapter 8.6 of this document.

8.1.7 Impact of Predictive control-based EMS for PV storage self-consumption optimisation

How the innovation affects the indicator: The deployment of the predictive control-based EMS includes a local control mechanism reacting to grid frequency deviations.

The reaction time to these grid frequency deviations will be lower than 30s (complete activation of the frequency reserve must occur within 30 seconds and cover a period of 15 minutes per incident according to ENTSO-E standards).

The formula/method used to estimate the indicator value: The reaction time to grid commands can be measured as the time between simulated grid frequency deviation measurement and output power activation.

8.1.8 Impact of Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)

How the innovation affects the indicator: The deployment of the real time commitment dispatch requires a local power output control mechanism (implemented as a standard feature in most of the PV inverters) controlled by a remote server receiving grid commands.

The reaction time to these grid commands will be lower than 20s (it is between level 1 and level 2 of the corresponding Grid indicator).

The formula/method used to estimate the indicator value: The demonstration stage will allow us to measure the reaction time to grid commands (cf “Response time” and “Gain” KPI of the presentations of WP6-8).

8.2 Obligation to participate in system services

Delivery of system services is obligatory for certain production units connected to the grid. These connection requirements are described in the European Network Code on Requirements for Generators (RfG). In addition, national legislation is often different in the European Member states. Examples of obligatory system services are voltage control and the obligation to disconnect from the grid at 50,2 Hz.

8.2.1 Impact of Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)

How the innovation affects the indicator:

The indicator is on high relevance to the demonstration about redispatch in Germany especially given that this is a mandatory requirement set by the state to all asset owners over 100 kW. This means that the assets have to be available to be turned off by the DSO or TSO if the grid situation requires. At the same time the aggregator is not allowed to steer against the signal.

The formula/method used to estimate the indicator value:

For this innovation the case of redispatch is special, given that in the way partner complies with the redispatch regulation does not mean that partner steers the assets according to signals from the TSO, which is the case for control reserve products. Instead, the DSO shuts down the asset at moments where the grid is congested for example. For partner the requirements are related to communication and settlement, which is detailed in D8.11.

8.2.2 Impact of Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)

How the innovation affects the indicator: The deployment of the real time commitment dispatch requires a local power output control mechanism (implemented as a standard feature in most of the PV inverters) controlled by a remote server receiving grid commands. These commands are computed from the network frequency value.

The reaction time to these grid commands has to be lower than 30s (in France). Which corresponds to level 3 of the indicator.

The formula/method used to estimate the indicator value: The demonstration stage will allow us to know if a PV system is able to deliver FCR. Details of the proposed method are available in deliverable "Documentation of the validation plan of Exploitable Results related to WP6".

8.3 Possibility to participate in market-based system services

Other grid services are voluntary and organized as a market or auction in which parties can voluntarily participate. Grid operators are often responsible to facilitate these grid services and organize these markets/auctions themselves and/or work together with (European) market platforms. Grid operators oblige participants in these markets to meet certain requirements and follow a prequalification process including simulations or pragmatic testing. The requirements can have a discriminatory character by excluding certain types of technologies, e.g. market entrance is only allowed for large (thermal) power plants or by excluding consumption installations. Technological requirements can also indirectly exclude PV power plants, e.g.: a required availability of 24h that excludes PV because of the inability to produce at night and forecast uncertainties. Examples of market-based grid services are reserve power provision (e.g. FCR, aFRR, mFRR), black start and congestion management.

8.3.1 Impact of Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)

How the innovation affects the indicator:

Partner aimed to demonstrate aFRR provision with a PV plant in the Netherlands, however, some problems were encountered. Instead of smoothly curtailing the asset, the controller abruptly shut down the inverters, causing a sudden, steep drop in production. This behavior suggests that the asset struggles to maintain continuous production during control commands, which is crucial for delivering aFRR services. This issue also raised uncertainty about whether production changes were due to the control signal or merely deviations from the forecasted output, highlighting challenges in accurately calculating a reliable PV baseline—a task for which market expertise remains limited, unlike for wind asses for example. This highlights that the possibility to participate in market-based services remains a challenge that no to the consortium known market party has solved.

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8.3.2 Impact of Operation of PV ensuring active power reserve available to provide ancillary services - grid connected

How the innovation affects the indicator:

The ER6_9 innovation, which enables photovoltaic plants to operate while ensuring an active power reserve for the provision of ancillary services, has a significant impact on the PPMS KPI.

The development of ER6_9 allows PV plants to manage their active power in a controlled manner and reserve part of that power to respond to grid demands. This capability enables participation in ancillary service markets, such as primary frequency regulation, where the involvement of PV plants has been limited due to the lack of adequate control mechanisms for maintaining an active power reserve.

With this innovation, PV plants are able to meet the requirements set by grid operators regarding power response and participation in these ancillary service markets, placing them on the same footing as other traditional technologies that currently dominate these markets.

As ER6_9 allows photovoltaic plants to participate in market-based system services under non-discriminatory conditions, it achieves a high level in the PPMS indicator. This reflects the fact that PV plants equipped with this innovation can participate in ancillary services markets on equal terms with other technologies, such as thermal or hydroelectric plants, meeting the technical and response criteria required by the system operator.

The formula/method used to estimate the indicator value:

Although the ER6_9 innovation does not directly provide a KPI that contributes to the PPMS indicator, it uses its own specific KPIs for performance evaluation. These KPIs assess the ability of the system to provide a stable power reserve and ensure compliance with grid requirements, which indirectly supports the plant's participation in market-based system services.

The specific KPIs used for the evaluation of ER6_9 include:

- Mean daily error: This KPI reflects the accuracy of the reserve estimation compared to the actual power reserve, helping to ensure that the plant can meet market commitments.
- Standard deviation: This measures the stability of the power reserve under fluctuating irradiance conditions, ensuring reliable participation in ancillary services.
- Sunrise/sunset overshoot: This KPI evaluates the system's behaviour during periods of rapidly changing solar output, ensuring that the reserve remains consistent during these critical moments.

While these KPIs are focused on the operational aspects of ER6_9, they provide valuable insights into the system's performance, which in turn supports the plant's ability to participate in market-based ancillary services, contributing indirectly to the PPMS KPI.

8.4 Availability of live data

Live data of PV power plants is essential to have a high forecast accuracy, which is often needed to provide (advanced) grid services such as provision of reserve power. It is used to evaluate if and how much system services a solar plant can provide in the next hours or days. The higher the resolution and the lower the delay of the transmission of the live data to the grid service provider, the better the forecast and the better the estimation of the available power to provide grid services.

8.4.1 Impact of Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)

How the innovation affects the indicator:

The availability of live data is highly relevant for the Redispatch (RD) process in Germany. RD data has consistently been available every quarter hour and gets updated several times before and during the RD call-offs. The data flow between operators might malfunction once per month for a short time due to a technical failure. However, the ratio for data availability is still high 99.8%

The formula/method used to estimate the indicator value:

For the calculation of data availability the number of hour in the evaluated period and the number of hours with a connection loss are needed and the calculation in conducted according to the formula below:

D: Total number of hours from 1 January – 31 August 2024: 244 Days x 24 hours = 5856 hours

d': Number of hours with a connection loss: 10 hours

$$\text{Data Availability: } \left(1 - \frac{d'}{D}\right) \times 100\% = 99.8\%$$

8.4.2 Impact of Automated data model integration framework for PV integration and communication in DSO data systems

How the innovation affects the indicator: The innovation will allow the advanced utilization of standardized data models and communication protocols to improve automation mechanisms interoperability, which further enables the standardized PV status monitoring or provision of grid-supporting measurements for DSO. The number of available parameters depends on the data model size and parameters included in the IEC 61850 reports. The temporal resolution of data transmission can be flexibly configured (e.g. 10s, 60s or 15 minutes). Regarding the innovation in ER6_2, the availability of live data (ALD) is in the range of **level 3 in the laboratory and level 3 in the field demonstration**.

The formula/method used to estimate the indicator value: a vital grid service indicator of ER6_2 is the Availability Live Data (ALD), which reflects the functionality relevant to PV monitoring, such as transmission interval and time delay.

For an IEC 61850 MMS telecommunication, the interval, or the temporal resolution, of live data transmission is configured as a fixed float number when enabling an IEC 61850 RCB, which strongly depends on the use case and data storage policy of the DSO.

While the temporal delay of transmitted can be measured by analyzing the traffic capture of the IEC 61850 communication. Note that the IEC 61850 server does not, like in the case of responding to control commands, use any additional IEC 61850 specific communication packet to answer back to a received IEC 61850 RCB packet. With this “restriction”, it is generally not possible to directly measure the RTT of a transmitted RCB, since the acknowledge packet from the IEC 61850 client will be the only information available, which is difficult to filter and trace.

To get rid of this restriction, the maximum round trip time (RTT) of all packets in the entire TCP/IP conversation can be used as an indicator of the maximum traveling time of live data packets in the IEC 61850 telecommunication, as calculated by the following formula:

$$Maximum\ TCP\ RTT = \max(RTT\ time\ of\ all\ TCP\ packets\ between\ the\ IEC\ 61850\ server\ and\ client)$$

This is a reasonable choice because large RTT values are likely to be caused by transmitting packets with large amounts of information, which is exactly what RCB packets do. Similarly, we can replace maximum by other statistical metrics. However, the IEC 61850 RCB packets can not be filtered out of all TCP packets, the average or median TCP RTT is not representative of the required transmission time of RCB packets because those packets are mixed with all the other TCP packets in the Wireshark capture, including small packets such as TCP keep-alive packets. Conversely, the 95% quantile value might deliver some information on the minimum or average RTT of IEC 61850 RCB.

Since the IEC 61850 server does not, like in the case of responding to control commands, answer back to any IEC 61850 RCB packets, it is generally not possible to directly measure the delay time. However, the maximum round trip time (RTT) of all packets in the entire TCP/IP conversation can be used as an indicator of the delay time of live data packets in the IEC 61850 telecommunication.

8.4.3 Impact of Digital twin of the grid with high PV contribution

How the innovation affects the indicator: The development of the digital twin requires live measured data as well as accurate synthesized (or simulated) consumption and production profiles to ensure an accurate state estimation of the grid. The availability of the grid means in this case obtaining the state estimation results. Assuming that the data will be available without a considerable delay in the corresponding data bank (e.g. InfluxDB), the time for obtaining the results is mainly the time required for the convergence of the state estimation algorithms. This time is usually in terms of few seconds for small a grid with few local area transformers (e.g. demo site Hittistetten). Therefore, the live data can be theoretically available in a temporal resolution of some seconds up to one minute level 2 to level 3. However, due to the specifications of PV and transformer monitoring platforms and availability of their real-time data, the grid digital twin performs real-time state estimation each 15 minutes, because they only allow a limited numbers of data calls. Therefore, the grid data are available, but not in the defined temporal resolution.

The formula/method used to estimate the indicator value: The time resolution set up in the grid digital twin environment defines the temporal resolution, or in other words the frequency of performing the state estimation. The digital twin environment can measure the time required for the convergence of the state estimation till the simulation results are available.

8.4.4 Impact of Further integration G2V into self-consumption optimisation software

How the innovation affects the indicator: partner has connected measuring hardware in the house of its customers (using mobile or ISP network). This hardware send data to own cloud to monitor the PV system, house and appliances consumption. The system can be configured to send data up to every few seconds or send every 15 minutes data of the last 15 minutes at a 2-second resolution.

The formula/method used to estimate the indicator value: We have internal tools that send command and do diagnostics of the system. You can check with them that you have access to the latest data within few seconds. We also have loggers that send data the Cloud that show this low latency (few seconds).

8.4.5 Impact of Implementation of IEC61850 for data communication on MV/LV grid

How the innovation affects the indicator:
One part of the IEC 61850 implementation is the direct integration of edge devices supporting different standard and non-standard protocols to a gateway for transmission towards a joined database. Within that a transformation to the IEC 61850 standard data model is committed to enable an easier and smoother data utilisation in other systems. As a result of this integration the availability of a huge variety of data in the IEC 61850 data model is made available as live data. The demonstration within the Living Lab Tobaj in Austria has generally shown **ALD Level 3** for data collection with a maximum temporal resolution of 1 second and a delay below 5 seconds and thus almost reaching **ALD Level 4**.

The formula/method used to estimate the indicator value:
The maximum resolution of the datasets is defined by the measurement devices and thus is set to 1 second values and thus is not changing the evaluation of the indicator. Based on that fixed value, the estimation is committed by an analysis of the average transmission and IEC 61850 transformation duration for the available datasets.

8.4.6 Impact of Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)

How the innovation affects the indicator: The deployment of the real time commitment dispatch requires an IT system that measures and transmits live data from the PV system. The live data are an estimation of the maximum power available and the network frequency. Each measure is performed 10 times per second and sent in less than 1s (it is level 3 of the corresponding grid indicator).

The formula/method used to estimate the indicator value: The demonstration stage will allow us to know if the measurement and transmission system are fast and accurate enough to provide FCR.

8.4.7 Impact of Service system for aggregating anonymous data for the monitoring and management of distributed generation systems

How the innovation affects the indicator:

The core functionality of ER6_8 enables real-time data from geographically dispersed self-consumption installations to be transmitted securely and anonymised into meaningful datasets. These datasets are then made available to the TSO or DSO through a secure API, ensuring that operators receive continuous and accurate live data. The use of IoT-based protocols ensures that data is transmitted with minimal latency, contributing to high ALD levels.

By making the live data from a wide range of installations consistently available and correctly anonymised, ER6_8 supports **Level 3 ALD**, where data is accessible in real-time and with a temporal resolution of less than one second. This ensures that grid operators can rely on this data for operational decisions, enabling faster and more accurate responses to changing grid conditions.

Additionally, the platform's ability to scale without compromising data transmission or integrity ensures that the ALD KPI remains stable even as the number of monitored installations increases. This level of data availability contributes significantly to the overall resilience and reliability of the grid, ensuring that live data from distributed energy resources is always available to those who need it.

The formula/method used to estimate the indicator value:

While the innovation ER6_8 does not directly provide formulas or methods for calculating the Availability of Live Data (ALD) KPI, it contributes to ensuring real-time data transmission and reliability through the specific KPIs designed to measure its performance listed in 8.6. These include data availability, integrity, and cybersecurity, all of which guarantee that the platform maintains a continuous flow of live data to TSOs and DSOs.

The real-time access to aggregated data, securely transmitted and anonymised, enables grid operators to make effective decisions, thus supporting Level 3 ALD. However, the precise estimation of this KPI falls outside the specific scope of ER6_8, as the platform enables live data transmission but does not directly control or enhance grid-wide data availability.

8.5 Specific KPIs for Task 6.3 – ER6_2

8.5.1 IEC 61850 and SunSpec Common Data Class Compatibility (CDCC)

How the innovation affects the indicator:

The formula/method used to estimate the indicator value:

The first KPI is defined specifically for this innovation regarding the compatibility with standard IEC 61850 and SunSpec data models, which mainly focuses on the following quantitative measures:

- Number of IEC 61850 data classes supported in the standard data model
- Number of SunSpec parameters included in the IEC 61850 – SunSpec matching table
- Number of SunSpec parameters read from the inverters
- Number of IEC 61850 parameters integrated into the DSO SCADA

To this extent, standardized parameters related to the operation of distribution grids are primarily of interest, e.g., feed-in active power, voltage amplitudes, phase currents, inverter status parameters, and configuration settings.

8.5.2 Data Availability (DA)

How the innovation affects the indicator:

The formula/method used to estimate the indicator value:

As ER6_2 provides DSO with the possibility of PV monitoring, KPI for data availability can be derived with these results. It is the fraction of time that the system delivers data divided by the time of the reference period, more specifically, for IEC 61850 Report Control Blocks (RCB) over a discrete temporal mesh grid with a certain transmission interval, the data availability is calculated using the formula:

$$Data\ Availability = \left(\frac{Number\ of\ MMS\ packets\ containing\ valid\ data}{Total\ number\ of\ MMS\ packets}\right) \times 100$$

It is only possible to derive the data availability when an IEC 61850 communication channel is active, and a method for data recording can be used. Wireshark packet captures or exports data archives from the SCADA database are examples of data recording.

8.6 Specific KPIs for Task 6.3 – ER6_8

8.6.1 Data Availability (Time-Based)

Description:

This KPI measures the percentage of data samples collected during a defined timeframe from a single installation, relative to the theoretical maximum number of samples. The theoretical maximum is calculated by multiplying the number of hours in the timeframe by the expected samples per hour (based on the monitoring resolution).

Formula:

$$Data\ Availability\ (Time - Based) = \left(\frac{Number\ of\ actual\ samples\ gathered}{Theoretical\ maximum\ number\ of\ samples}\right) \times 100$$

A 100% availability indicates that no gaps exist in the dataset, while lower percentages may indicate communication issues, downtime, or other interruptions in the data flow.

8.6.2 Data Availability (Monitoring Panel-Based)

Description:

This KPI measures the percentage of inverters that successfully send their data in a given moment, relative to the total number of inverters being monitored.

Formula:

$$Data\ Availability\ (Panel - Based) = \left(\frac{Number\ of\ inverters\ providing\ data}{Total\ number\ of\ inverters\ in\ the\ monitoring\ panel}\right) \times 100$$

100% availability indicates that all monitored inverters are actively sending data.

8.6.3 Data Anonymisation Accuracy

Description:

This KPI measures the accuracy of the anonymisation process, ensuring that the data shared with DSOs and TSOs does not reveal individual prosumer details, while still providing useful insights into energy production at an aggregate level.

Formula:

$$Data\ Anonymisation\ Accuracy = \left(\frac{Instances\ where\ data\ remains\ anonymous}{Total\ data\ points\ shared}\right) \times 100$$

100% anonymisation accuracy means that all data shared with operators remains fully anonymous.

8.6.4 Zone Location Conformance Ratio

Description:

The Zone Location Conformance Ratio measures the accuracy of the system in correctly grouping plants (photovoltaic installations) with location information into their respective geographical zones. It ensures that the data being aggregated is accurately associated with the correct geographical areas, which is critical for the system's ability to provide reliable and actionable insights to DSOs and TSOs.

Formula:

$$Zone\ Location\ Conformance\ Ratio = \left(\frac{Number\ of\ plants\ correctly\ grouped\ by\ geographical\ zone}{Total\ number\ of\ plants\ expected\ in\ that\ zone}\right) \times 100$$

A 100% ratio indicates that all plants are correctly assigned to their respective zones, whereas lower percentages suggest mismatches or data inaccuracies.

8.6.5 Scalability

Description:

The Scalability KPI measures how efficiently the system can grow in the number of connections it can handle without requiring an increase in resources (such as databases, brokers, or processing servers). The key factor is determining how close the system is to its resource limits before performance degrades and identifying when additional resources (e.g., additional brokers) must be added.

The system's performance begins to degrade (typically detected through data loss) once any resource reaches its capacity limit. This KPI ensures that system resources are scaled efficiently and prevents costly oversizing.

Independent Limiting Factors:

- **Database Size**: The total volume of data that the system can store before performance slows down or data is lost.
- **Broker Capacity**: The number of simultaneous connections that the message broker can handle.

- **Processing Server Capacity**: The system's ability to process incoming data and distribute it to relevant subscribers.

Formula:

For each resource, a separate formula is used to quantify its current usage as a percentage of its maximum capacity.

$$Database\ Scalability\ (DBS) = \left(\frac{Current\ Database\ Size}{Maximum\ Database\ Size}\right) \times 100$$

$$Broker\ Scalability\ (BS) = \left(\frac{Current\ Number\ of\ Connections}{Maximum\ Broker\ Capacity}\right) \times 100$$

$$Processing\ Server\ Scalability\ (PSS) = \left(\frac{Current\ Processing\ Load}{Maximum\ Processing\ Capacity}\right) \times 100$$

100% in any of these formulas would indicate that the resource has reached its capacity, and oversizing (e.g., adding another broker or increasing processing server capacity) would be necessary.

8.6.6 Cybersecurity Events

Description:

This KPI tracks the number of cybersecurity incidents (e.g., breaches, unauthorised access attempts, data manipulation) detected and mitigated by the system.

Formula:

$$Cybersecurity\ Events = \frac{Detected\ and\ mitigated\ incidents}{Total\ security\ events}$$

8.7 Specific KPIs for Task 6.4

Table 8.3: Specific KPIs for Task 6.4

Grid indicators	Level 1	Level 2	Level 3
Estimation of voltage deviation	Estimation not possible	Estimation with error > 1%	Estimation with error < 1%
Estimation of grid loading	Estimation not possible	Estimation with error > 1%	Estimation with error < 1%

8.7.1 Estimation of voltage deviation KPI

How the innovation affects the indicator: The value of voltage deviation comes as a result of the state estimation. The accuracy depends on the number of measuring points and the accuracy of the measurements. The present version of the grid digital twin corresponds likely to level 2 (see Table 8.3).

The formula/method used to estimate the indicator value: The accuracy of the voltage deviation value will be measured by a comparison between the simulation value and the measured value. The estimation of the voltage deviation is calculated using the formula:

$$Estimation\ Error = \frac{Measured\ value - Simulated\ value}{Measured\ value} \times 100$$

8.7.2 Estimation of grid loading KPI

How the innovation affects the indicator: The value of grid loading comes as a result of the state estimation. The accuracy depends on the number of measuring points and the accuracy of the measurements. The present version of the grid digital twin corresponds likely to level 2 (see Table 8.3).

The formula/method used to estimate the indicator value: The accuracy of the voltage deviation value will be measured by a comparison between the simulation value and the measured value. The estimation of the voltage deviation is calculated using the formula:

$$Estimation\ Error = \frac{Measured\ value - Simulated\ value}{Measured\ value} \times 100$$

9 Conclusions

This report summarised the innovations developed in the SERENDI-PV project and briefly explained the key performance indicators introduced in task 1.1 of working package 1 of the project and publicly shared in D1.1 [1]. The purpose of the report was to measure and quantify the actual impact of the SERENDI-PV innovations on the selected key performance indicators (KPIs) based on the outputs of the innovations demonstrations. The number of KPIs which were measured and quantified as part of demonstrations was much lower than the number of KPIs which were expected to be affected by the innovations in the mid-term report. Though partner expectations presented in the mid-term report were reasonable and supported by explanation of the mechanism of potential impacts, in many cases it was not possible to collect necessary data at demonstrators, or it was not possible to collect enough data within the SERENDI-PV project lifespan.

For the final report the KPIs were additionally subdivided into technical KPIs and general KPIs categories. Technical KPIs include the KPIs which have impact on the performance of specific equipment and can be directly measured with existing equipment and standard methods. General KPIs have impact on the overall performance of the PV systems and demand assessment of not only the developed element but of the whole PV system, for such KPIs the direct measurements often are not possible within the scope of the project and the KPIs values were estimated based on technical KPIs and/or additional assumptions.

Technical KPIs were measured at demonstrators for innovations according to their applicability and summarised for individual WPs in WP8 reports. This report summarises technical KPIs from the WP8 reports and provides information about location of detailed data on the innovation demonstration and the presented KPIs measurements. Unfortunately, some of the applicable technical KPIs, which were expected to be presented in this report, were not integrated in the WP8 deliverables, or were not measured despite initial plans. Some of technical KPIs chosen for the SERENDI-PV project have proven to be inapplicable or impossible to measure within the project. For example, Performance Loss Rate was found applicable and was measured only for WP3 innovations, Forecast Skill Score was not measured for any of the project innovations. Available technical KPIs proved improvements thanks to SERENDI-PV innovations, however, as it is described in individual innovations specific WP8 deliverables, the impact of innovations varies for different locations and other conditions.

General KPIs were impossible to directly measure within the project, but with help of the technical KPIs measurements and the experience from the demonstrators operation it was possible to estimate impact of the innovations on the chosen KPIs. Many of the general KPIs are connected and depend on each other. From the list of general KPIs chosen for SERENDI-PV in D1.1, Performance Ratio and Weighted Average Cost of Capital are most important as these affect all other general KPIs. Most of the innovations were found to impact the general KPIs, mostly through impact on Performance Ratio and the WACC.

Performance Ratio was seen as the most important impact of the developed innovations, however within the project it was defined that the innovations may have more significant impact via WACC reduction. The innovations help to reduce losses, avoid faults and consequently slightly increase the performance of the system, however impact on uncertainty of a project will be more important, since minor change of WACC has a much higher impact on LCoE and NPV.

Temperature-corrected Performance Ratio was found irrelevant for the project innovations, as this expected impact must be uniform for the whole range of operating temperatures of the system, consequently impact on Temperature-corrected Performance Ratio will be equal to impact on real Performance Ratio.

Innovations were found to have limited impact on (Modified) Internal Rate of Return. The observed improvement of Performance Ratio is not big enough to have sensible impact on (Modified) Internal Rate of Return considering 30 years lifetime of the PV modules assumed in the general KPIs calculations.

Grid KPIs were found not detailed enough for the variety of innovations developed within WP6. For some innovations the detailed explanations were added to better frame the KPI for the innovations, finally additional KPIs were provided to better assess the impact of the innovations on the grid and PV system interactions.

Figure 9.1 summarises the applicability of KPIs and impact of individual innovations on the KPIs defined for the SERENDI-PV project.

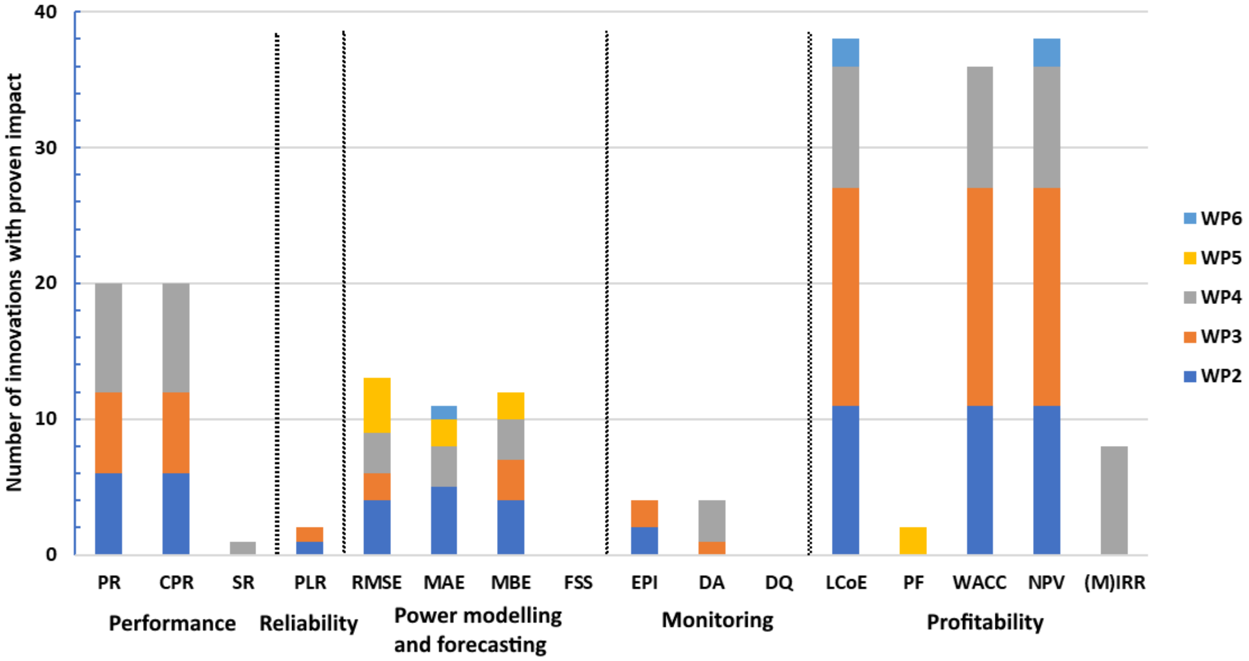

Figure 9.1: Number of potentially influential SERENDI-PV innovations per key performance indicator.

The results prove that the innovations developed within the SERENDI-PV project have a positive impact on the key KPIs for solar PV systems, enabling more efficient operation of PV systems (PR), higher profitability (NPV), and lower electricity cost for the system and electricity users (LCoE).

10 Appendix

Table 10.1: Technical and General KPIs overview

ID	Innovation	Performance			Reliability	Power modelling & forecasting				Monitoring			Profitability				
		PR	CPR	SR	PLR	RMSE	MAE	MBE	FSS	EPI	DA	DQ	LCoE	PF	WACC	NPV	(M)IRR
2.1	Modelling of bifacial PV systems	X	X			X	X	X		X			X		X	X	
2.2	Modelling of floating PV systems	X	X			X	X	X					X		X	X	
2.3	Modelling of small PV systems, including building attached PV (BAPV)	X	X			X	X	X		X			X		X	X	
2.4	Modelling of building integrated PV (BIPV) systems, any size	X	X			X	X	X		X			X		X	X	
2.5	Modelling of soiling	X	X			X	X	X		X			X		X	X	
2.6	Modelling of snow	X	X			X	X	X		X			X		X	X	
2.7	Modelling of degradation				X		X	X					X		X	X	
2.8	Load profiles generation for self-consumption evaluation												X		X	X	
2.9	Modelling of uncertainty and variability and implementation into financial models												X		X	X	
2.10	Analytically tracking uncertainty propagation in financial models with probability density functions						X						X		X	X	
2.11	Consideration of the long-term evolution of the solar resource to address gaps in traditional Long-Term Yield Assessments												X		X	X	
3.1	Specific data analytics for bifacial PV systems				X			X		X	X	X	X		X	X	

ID	Innovation	Performance			Reliability	Power modelling & forecasting				Monitoring			Profitability				
		PR	CPR	SR	PLR	RMSE	MAE	MBE	FSS	EPI	DA	DQ	LCoE	PF	WACC	NPV	(M)IRR
3.2	Specific data analytics for floating PV systems				X	X		X		X	X	X	X		X	X	
3.3	Specific data analytics for small PV systems, including BAPV												X		X	X	
3.4	Specific data analytics for BIPV systems, any size					X		X					X		X	X	
3.5	Specific data analytics for soiling	X	X	X	X					X	X	X	X		X	X	
3.6	Specific data analytics for vegetation				X								X		X	X	
3.7	Specific data analytics for snow				X					X	X	X	X		X	X	
3.8	Specific data analytics for degradation				X					X	X	X	X		X	X	
3.9	IR imaging data analytics	X	X		X								X		X	X	
3.10	Failure detection and diagnosis methods	X	X										X		X	X	
3.11	Fault detection/diagnosis toolbox for small PV												X		X	X	
3.12	PV inverter efficiency characterisation												X		X	X	
3.13	Predictive diagnosis of inverter temperature anomalies	X	X										X		X	X	
3.14	PV inverter digital twin	X	X							X			X		X	X	
3.15	PV battery digital twin												X		X	X	
3.16	BIPV digital twin	X	X							X			X		X	X	
3.17	Quality control system for identification of incorrect data from PV power plants				X					X	X	X					
4.1	Specific procedures for bifacial PV systems					X				X							
4.2	Specific procedures for floating PV systems																

ID	Innovation	Performance			Reliability	Power modelling & forecasting				Monitoring			Profitability			
		PR	CPR	SR	PLR	RMSE	MAE	MBE	FSS	EPI	DA	DQ	LCoE	PF	WACC	NPV	(M)IRR
4.3	Hardware in the Loop Platform for testing large inverters in the laboratory	X	X										X		X	X	
4.4	New procedures for PV inverters field testing	X	X			X	X	X			X		X		X	X	
4.5	Procedure for PV inverters MPPT testing																
4.6	Procedure for measuring MPPT efficiency in the field	X	X			X	X	X			X		X		X	X	
4.7	Operating conditions measuring kit					X	X	X			X		X		X	X	
4.8	Soiling measurement kit	X	X	X		X	X	X			X		X		X	X	
4.9	Lab-testing for soiling analysis and cleaning assessment (related to the soiling kit)																
4.10	Lab-testing protocol for accelerated ageing reliability qualification tailored to floating and bifacial PV																
4.11	capacitive I-V tracer at 1,500V	X	X			X	X	X			X		X		X	X	
4.12	New procedures for batteries field testing	X	X			X	X	X			X		X		X	X	
4.13	Procedure for measuring ageing rates in PV modules in the field	X	X			X	X	X			X		X		X	X	
4.14	Procedure for measuring the I-V curve of bifacial PV modules in the field	X	X			X	X	X			X		X		X	X	
5.1	Short-term PV power forecasting based on the integration of satellite data and Numerical Weather Prediction (NWP) models with PV power production data (small and medium-sized PV systems)													X			

ID	Innovation	Performance			Reliability	Power modelling & forecasting				Monitoring			Profitability				
		PR	CPR	SR	PLR	RMSE	MAE	MBE	FSS	EPI	DA	DQ	LCoE	PF	WACC	NPV	(M)IRR
5.2	PV power nowcasting by merging satellite data with sky-camera data and methods for PV power output aggregation					X	X	X	X								
5.3	Improved power forecasting in presence of snow, dust, fog, and other extreme events																
5.4	Forecasting applied to bifacial PV systems					X	X	X									
5.5	Forecasting applied to floating PV systems					X	X	X									
5.6	Forecasting applied to residential PV systems													X			
5.7	Forecasting for spatial averaging and PV aggregation					X	X	X									
6.1	Real-time Control and Marketing System enabling the participation in grid relieving operations by a pool of PV plants (without storage)										X	X		X		X	
6.2	Automated data model integration framework for PV integration and communication in DSO data systems																
6.3	Digital twin of the grid with high PV contribution																
6.4	Further integration G2V into self-consumption optimisation software						X						X				
6.5	Implementation of IEC61850 for data communication on MV/LV grid										X	X					
6.6	Predictive EMS for PV storage self-consumption												X			X	

ID	Innovation	Performance			Reliability	Power modelling & forecasting				Monitoring			Profitability				
		PR	CPR	SR	PLR	RMSE	MAE	MBE	FSS	EPI	DA	DQ	LCoE	PF	WACC	NPV	(M)IRR
6.7	Real time commitment dispatch and IT system for down FCR participation of PV plants (without storage)																
6.8	Service system for aggregating anonymous data for the monitoring and management of distributed generation systems (residential, commercial and small industry).										X	X					
6.9	Operation of PV ensuring active power reserve available to provide ancillary services - grid connected.						X										

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