Best practices for optimal PV performance

Enhancing Performance and Reliability on Photovoltaic System Level – Recommendations for Industry and Service Providers

PERFORMANCE PLUS

COORDINATOR

PROJECT PARTNERS

USERS GROUP

A user group – composed of large portfolio owners and strong EPC and O&M contractors supported the consortium and provided valuable validation and input on results. The six members of the Users Group of the *Performance Plus* project are :

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3E

3E is a technology company in sustainable energy. It provides consultancy and software to improve the performance of renewable energy portfolios, to reduce energy consumption and to facilitate grid and market interaction. 3E's expertise covers solar energy, wind energy, sustainable buildings and sites, power infrastructure and energy markets. The company can count on the experience of 100 experts, with references in 40 countries. 3E's clients include project developers and investors, power utilities and grid operators, technology manufacturers, asset managers, maintenance companies and public authorities.

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PROJECT PARTNERS

AIT Austrian Institute of Technology GmbH

AIT Austrian Institute of Technology GmbH is Austria's largest non-university research organisation with more than 900 employees. In the field of electricity networks and distributed energy resources AIT's main expertise is in low and high voltage technology, power quality, safety and reliability analysis. AIT has long term experience in active integration of distributed generation in distribution networks and related applications. Furthermore, AIT is represented in several technology platforms and is involved in the European Electricity Grid Initiative (EEGI), the EERA Joint Programmes on Smart Grids and PV and several Implementing Agreements of the International Energy Agency (ISGAN, IEA-PVPS).

www.ait.ac.at

Carl von Ossietzky Universität Oldenburg

The University of Oldenburg is well known for its Renewable Energy research and education for several decades. Currently around 150 scientists are working on Renewable Energy, mostly within the Institute of Physics. The Energy Meteorology group with more than 20 scientists investigates the influence of weather and climate on energy supply systems with increasing contributions from solar and wind energy. Within this field, forecasting of both wind and solar power generation, modelling of wind resources on various scales, satellite-based estimation of surface solar irradiance, and solar spectral modelling are major topics. For PV applications the group participated in several EU projects and numerous national research projects.

www.uni-oldenburg.de

PROJECT PARTNERS

Alitec SRL

Established in 2006, Alitec SRL is a research and development company in the fields of mechanics, electronics, photonics, optics and software. Alitec's main objective is to create original and technologically advanced solutions that have high added-value and limited costs. Alitec is present in the industrial areas of renewable energy, energy efficiency, monitoring & control, process industry, health & safety and data centers. Alitec's team consists of physicists, engineers and computer scientists with solid experience. Alitec has scientific contacts and collaborations with many Italian and international universities and research centres. Alitec is a partner of PHORIT and Photonics21, respectively the Italian and European technology platforms that bring together the most innovative companies and research centres working in the field of photonics, and of the Italian Technology Platform on Concentration Solar.

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Katholieke Universiteit Leuven

KU Leuven boasts a rich tradition of education and research that dates back six centuries. The basic research orientation has always been and will remain fundamental research. At the same time, the university remains vigilantly open to contemporary cultural, economic and industrial realities, as well as to the community's needs and expectations. KU Leuven is currently by far the largest university in Belgium in terms of research funding and expenditure (EUR 418 million in 2013), and is a charter member of LERU. KU Leuven conducts fundamental and applied research in all academic disciplines with a clear international orientation. KU Leuven Research & Development (LRD) is the technology transfer office, where a multidisciplinary team of experts guides researchers in their interaction with industry and society, and the valorisation of their research results (101 spin offs, ...) .
KU Leuven's contribution to *Performance Plus* comes from the research group Thermal Systems (TS) which has shown that significant energy savings can be reached by using model based predictive control (MPC) strategies for thermal systems.

www.kuleuven.be

PROJECT PARTNERS

IMEC – Interuniversitair Micro-electronica Centrum VZW

IMEC performs world-leading research in nano-electronics. IMEC leverages its scientific knowledge with the innovative power of its global partnerships in ICT, healthcare and energy. IMEC's goal: creating innovative solutions that are relevant for the industry. IMEC's research is 3 to 10 years ahead of the industry. IMEC forms a bridge between the fundamental research at universities and the technology development in the industry. IMEC is headquartered in Leuven, Belgium. It has additional R&D teams in the Netherlands (Holst Centre in Eindhoven), PR China, Taiwan, and India, and offices in Japan and the USA. IMEC's staff of over 2,200 people includes more than 600 industrial residents and guest researchers. In 2014, IMEC's revenue (P&L) was over 330 million euro.

www2.imec.be

Scuola Universitaria Professionale della Svizzera Italiana (SUPSI)

The Institute for Applied Sustainability to the Built Environment (ISAAC) is part of the University of Applied Sciences of Southern Switzerland (SUPSI). The institute's research activities cover renewable energy (photovoltaic and geothermal), rational use of building energy with particular attention to green building standards, building maintenance and refurbishment and environmental studies. The PV department has almost 30 years of experience and employs around 20 people today. The research and offered R&D services focus on performance testing, life-time testing and energy rating testing of PV modules as well as monitoring of PV systems and smart grid applications. The research has also led to several spin-off activities. In 2005, the Centre of Competence for Building Integrated Photovoltaics (BIPV) was funded and in 2009 the Swiss PV Module Test Centre covering the whole range of electrical, climatic and mechanical tests according to IEC standards IEC 61215, IEC 61646 and IEC 61730 (accredited ISO 17025) was launched.

www.supsi.ch

SUPPORTED BY

Users Group

The Users Group of the *Performance Plus* project is composed of six members, large portfolio owners and strong EPC and O&M contractors supported the consortium and provided valuable validation and input on results.

European Union

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A

Executive Summary

Enhancing Performance and Reliability on Photovoltaic System Level – Recommendations for Industry and Service Providers

Enhancing the performance, reliability and lifetime of commercial photovoltaic systems

The Photovoltaic (PV) industry has made large technological progress with PV cells, modules and inverters in terms of costs and reliability. However, from an integrated perspective, PV system performance emerges from, but is not limited to, the performance of the components. Therefore, in order to ensure a continued decrease of the costs linked to electricity from PV, the performance, functionality, reliability and lifetime on the system level need to be improved. The predicted PV performance as calculated by different PV performance modelling software packages available on the market can differ significantly between each other and from the actual performance from real systems. One of the main goals of *Performance Plus* was to better understand these discrepancies between predicted and actual performance of PV systems and to provide new models, methods and tools to overcome these limitations. During the operational phase of a PV plant, the early detection and diagnosis of faults are of the utmost importance to obtain and maintain high energy production. Furthermore, the timely remediation of faults not only restores the production promptly, but also avoids the occurrence of additional component failures and leads to the reduction of costs for operation and maintenance (O&M). However, this early and reliable detection of issues requires accurate models of the expected behaviour of the well-performing PV plant. In practice, tools are required to help PV plant owners and operators in reducing the occurrence of component failures and thus reducing O&M costs. The *Performance Plus* project has developed models, test procedures and tools that provide insight in the root causes of performance losses of PV systems.

In order to increase the sales value of the PV electricity for the owner or an aggregator acting as intermediary, PV is increasingly becoming integrated with on-site storage and energy management systems. This requires accurate short-term PV yield forecasts and optimal control. Suboptimal control may cause unnecessary over-sizing of storage devices or a significant drop of the overall energy conversion efficiency of the PV-energy management-storage system. The consortium has implemented and validated a model predictive control (MPC) for the application of different use cases for optimal control of thermal systems and storage.

The Performance Plus Project

The main goal of the *Performance Plus* project was to develop and demonstrate models and tools to monitor, control and test PV plants. These models, methods and tools would then be used to optimize and enhance the performance, reliability and lifetime of commercial PV systems. Means for a better integration of PV-generated electricity into the power system were provided by methods for short-term forecasting, PV system monitoring, testing and integrated energy management and storage control.

The *Performance Plus* project looked at how to improve the PV system as a whole rather than on component level. Therefore, the PV modules and inverters were studied with focus on their operation within a system. Moreover, the discrepancies between predicted and actual performance of PV systems were studied. The consortium analysed the way the uncertainties of all input parameters propagate throughout the PV modelling chain and affect the predicted performance. The developed models, methods and tools aiming at reducing these uncertainties focus on the early and reliable detection of operational performance issues by providing insight on the root causes of performance losses. This knowledge will help PV plant owners and operators to reduce the occurrence of component failures, and thus reduce their O&M costs.

All models were validated with empirical data and the resulting tools were demonstrated in a relevant environment. The *Performance Plus* consortium used monitoring data from a total of 25 PV systems across Europe. The available PV plants cover a wide range of installation capacity, from small residential-scale systems to large utility-scale PV plants, and are distributed over Europe.

Conclusion and Recommmendations

The *Performance Plus* project has developed models, methods and tools to optimize and enhance the performance, reliability and lifetime of commercial PV systems. All results were validated and demonstrated with empirical data from a total of 25 PV systems across Europe. Novel methods have been introduced and validated for advanced PV module modelling, short-term forecasting, testing and diagnostics, advanced PV system monitoring techniques and integrated energy management and storage control. Some of these project results are already being transformed into proven marketable products. The results of the validation and demonstration phase as well as many other documents are available on the project website:

www.perfplus.eu

PV PLANT DESIGN

The financial risk assessment of a PV project directly depends on the uncertainty of the underlying business plan. In order to help developers and investors to evaluate more carefully the financial risks during the design phase of the PV plant, the *Performance Plus* consortium recommends to always perform a quality control of the data and to properly assess and report the related uncertainties. The assessment of the solar resource has been identified as the most important element in the contribution to the total uncertainty. Therefore, if appropriate, the consortium recommends combining ground measurements and satellite estimates in order to reduce the uncertainty of the solar resource assessment.

For situations where a high accuracy of the modelled output power is required, the use of fine-grain thermo-electric models is recommended to account for the effect of non-uniform and fast changing ambient conditions. Furthermore, as the PV inverter plays a key role in the power conversion chain of the PV system, the consortium recommends performing additional tests to help to characterise the performance related impact of the PV inverter working under non-ideal conditions. Additional accelerated stress reliability tests can help to qualify PV inverters for real world applications under different climate conditions.

For better understanding and estimating the long-term energy performance of PV modules, new indoor test procedures for degradation mechanisms have been introduced. The procedures will allow for determining the tendency of performance degradation mechanisms caused by potential induced degradation (PID) and dynamic load stress during the PV module's lifetime. These new procedures continue under development within the respective working groups of the International Electrotechnical Commission (IEC).

PV PLANT OPERATION

An innovative sensor that measures global, diffuse and direct irradiance has been developed within the project. The developed irradiance sensor, called ESA, significantly improves both the costs and the ease of operability in the measurements of solar irradiance. The reduced costs and maintenance efforts allow not only for small PV plants to perform solar irradiance monitoring, but also for medium to large PV plants to perform distributed rather than single-point monitoring. Furthermore, in the field of energy management and optimal control of thermal systems, the ESA sensor enables the active optimization and fine-tuning of heating and/or cooling related energy use.

Departing from operational data, the *Performance Plus* project has developed a methodology able to provide insight in the root causes of performance losses of PV plants. This methodology, called PV *Health Scan*, allows the systematic analysis of operational data in an efficient way, identifying how design choices and O&M practices lead to inferior or on the contrary, superior performance in the field. Demonstration results show that, thanks to the application of the PV *Health Scan* methodology, the performance could be increased significantly (by 10% and more) for some PV plants.

A set of procedures and tools for testing PV system in the field has been developed within the project. The methods have been designed to detect issues in underperforming PV plants. , They have led to tools for improved laboratory testing and tools for outdoor testing of PV plants. The tools for laboratory testing focus on an improved PV module sampling procedure with a clear definition of number of PV modules to test, selection of modules and a final lot acceptance report. Furthermore, the procedures and tools for PV system field testing aim at detecting different modes of degradation (PID, optical, electrical or mechanical damage) using traditional light *I-V* curve measurement and innovative dark *I-V* measurement techniques. Also methods for differentiating between failures and degradation modes that can happen in operational PV plants were developed by the consortium.

ENERGY MANAGEMENT AND CONTROL

As an enabling technology for energy management and control, the *Performance Plus* consortium has investigated and improved short-term solar power forecasting with different methods and forecast horizon. The consortium investigated the combination of different forecast models to further reduce the forecast error of the solar resource. Furthermore, the consortium has focused on irradiance forecasting using sky imagery. The overall results of the validation show that sky image analysis provides very high-resolution binary cloud masks, but has limitations in deriving aerosol and cloud optical properties. However, as no expensive radiometric measurement devices are required, the proposed approach significantly reduces the initial investment and operational costs. For PV power forecasting or nowcasting purposes, the consortium has developed a technique that significantly speeds up the computation without compromising the accuracy. The developed model uses a combination of a one-time a-priori scenario clustering phase and a continuously executed scenario detection phase during operation. The results show that this approach is more suitable than state-of-the-art methods, especially under highly variable weather conditions and for short forecasting windows. For remote control of PV inverters, the consortium has introduced and implemented a cost effective way of upgrading state-of-the-art PV inverters through a standard-compliant gateway device. The first test results of the gateway controller were successful in both laboratory and operational test setups. However, reliability problems appeared after several hours of operation in the operational test setup. Nevertheless, since the proposed solution uses an open source implementation, further development and validation of it in a more complex real world demonstration scenario is encouraged by the consortium.

As approach for efficient energy management and storage control, the *Performance Plus* consortium has successfully demonstrated MPC. This ensures the overall optimization of systems comprising PV, controllable thermal energy resources and possibly storage. The overall results show that accurate modelling of such systems is essential for the application of optimal control methods. For accurate yet fast modelling of the thermal systems for optimization, the so-called Grey-box toolbox has been developed. The MPC along with an adapted grey-box model was successfully demonstrated on the 3E headquarters office building in Brussels. Results show that the use of MPC during the winter in Belgium allows saving up to 30% of the heating energy costs compared to the initially used rule based controller. Furthermore, combined with PV, the MPC allows to harness flexibility from any controllable load. The results show that the use of MPC can improve the energy management of a cold store warehouse by optimally pre-cooling the building with PV generated power. The results of the implementation of different use cases show that the MPC allows integrating optimal design choices (e.g., battery sizing) with the optimal control of the system.

TAKEAWAYS

The essential takeaways are summarized in the bullet points below. These takeaways are divided in three subsections according to the structure of this report.

PV PLANT DESIGN

- The assessment of the solar resource has been identified as the most important element in the contribution to the total PV modelling uncertainty;

- The *Performance Plus* consortium recommends to always perform a quality control of the measured/estimated irradiance data and to properly assess and report the related uncertainties;

- If appropriate, ground measurements and satellite estimates should be combined as described in [1], in order to reduce the uncertainty of the solar resource assessment;

- For situations where a high accuracy of thepower generation of a PV array is required in space and time (e.g., for module-level inverter applications), the use of fine-grain thermo-electric models as described in [2]–[5] is recommended;

- Fine-grain transient models for the PV micro-inverter should be integrated in the PV module model to reach the fully achievable accuracy;

- By using the measured parameters obtained during the inverter test procedures recommended by the consortium in [6], potential issues during the PV plant design phase as well as degradation and aging issues during operational phase can be identified;

- The new indoor test procedures proposed by the consortium in [7] will allow to determine the tendency of performance degradation mechanisms caused by PID and dynamic load stress during the PV modules lifetime;

- The specific set of test procedures intended for PV inverter lifetime performance evaluation described in [8] allow to qualify the inverter design for a real world application under different climate conditions;

- The lifetime expectancy of PV inverters can be assessed by using the measured parameters obtained during the tests described in [8];

- Cost-efficient integration of the different PV system components can be reached through a holistic cost optimization approach by using a tool that combines advanced PV models as described in [9].

PV PLANT OPERATION

- In order to maximize PV plant yield and minimize O&M costs, the continuous monitoring of both actual power output and solar irradiance is crucial;

- The costs and the ease of operability in measurements of solar irradiance components (i.e. direct normal and diffuse irradiance) are significantly improved by the developed ESA irradiance sensor compared with an equivalent solar irradiance measurement station;

- The ESA sensor allows not only for small PV plants to perform solar irradiance monitoring, but also for medium to large PV plants to perform distributed rather than single-point monitoring;

- In the field of energy management and optimal control of thermal systems, the ESA sensor improves the forecasting and control of heating and/or cooling related energy use;

- The PV *Health Scan* enables the identification of root causes affecting the performance of a PV system. The methodology allows for identifying how design choices and O&M practices lead to inferior or, on the contrary, superior performance in the field;

- For some cases it was shown, thanks to the PV *Health Scan* methodology, that solving the identified issues could increase the performance of the PV plant by 10% and more;

- The new developed procedures and tools will help to improve laboratory testing and to detect issues in PV plants affected by under performances;

- The proposed dark *I-V* curve field measurements should be coupled with the traditional light *I-V* curve measurements.

ENERGY MANAGEMENT AND CONTROL

- The use of inexpensive sky imagers for the observation of the atmospheric state is a valuable addition to meteorological measurements and allows shortest-term irradiance forecasts;
- Accurate irradiance forecasts require a combination of different data sources and forecasting models to consider the large variability of solar irradiance;
- The use of MPC during the winter in Belgium allows saving up to 30% of the heating energy costs compared to the initially used Rule Based Controller (RBC);
- Combined with PV, the MPC allows harnessing flexibility from any controllable load;
- The use of MPC can improve the energy management of a cold store warehouse by optimally pre-cooling the building with PV generated power;
- The MPC allows integrating optimal design choices (e.g., battery sizing) with the optimal control of the system. It is therefore very well suited for efficiently realizing storage control and energy management with thermal systems and PV.

Contents

Symbols and Abbreviations

AC	Alternating Current
BOS	Balance of Systems
COP	Coefficient of Performance
DC	Direct Current
EPIs	Energy Performance Indices
GHI	Global Horizontal Irradiance
IEC	International Electrotechnical Commission
I_{sc}	Short Circuit Current
LCOE	Levelized Cost of Energy
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
MSG	Meteosat Second Generation
nRMSE	Normalized Root Mean Squared Error
nMAE	Normalized Mean Absolute Error
nMBE	Normalized Mean Bias Error
O&M	Operation and Maintenance
PID	Potential Induced Degradation
POA	Plane-of-array
PR	Performance Ratio
PV	Photovoltaic
RBC	Rule Based Control
R_s	Series Resistance
R_{sh}	Shunt Resistance
SPVMTC	Swiss PV Module Test Center
STC	Standard Test Conditions
V_{oc}	Open Circuit Voltage

1. Introduction

1

Introduction

This report describes the best practices for improving the performance and reliability of photovoltaic (PV) plants on the system level. It has specially been written for industry professionals, service providers and researchers who are active in PV system integration and the downstream segments of the value chain. These best practices are based on conclusions and recommendations from the Performance Plus project.

A detailed description of the validation and demonstration results are available in the technical reports Demonstration and *Validation Report for Sensor and Monitoring System* [10] *and Demonstration and Validation Report of Tools for Field Testing* [11].

Additional reports and publications are available on the project website:

perfplus.eu.

Beyond Improving Components: System Level Optimization

The PV industry is today at an interesting point in its history. To ensure a continuous decrease of the costs linked to electricity from PV, the prices of modules, inverters and balance of system (BOS) components have to be further decreased. This has to be accomplished, while performance, functionality, reliability and lifetime on the component and system level need to be increased. Needless to say, the industry has made large technological progress with PV cells, modules and inverters in terms of costs and reliability. However, from an integrated perspective, PV system performance emerges from, but is not limited to, the performance of the components. Therefore, in order to improve the performance of PV systems, we need to look at how we can improve the system as a whole.

Limitations during Design Phase: Predicted vs Real Performance

There are several PV performance modelling software packages available on the market, specially developed to predict the amount of energy that a PV system can produce. The predicted performance from these models can differ significantly between each other and from actual performance from real systems. One of the main goals of this work was to better understand these discrepancies between predicted and actual performance of PV systems.

The large amount of input parameters like irradiance, temperature, array orientation, module and inverter performance, user-defined values for additional losses such as soiling, mismatching, cabling, etc. have inherent uncertainties. These uncertainties have to be properly taken into account, as their correct quantification is essential for evaluating the financial risk of PV investments.

Improving Operation & Maintenance: Early and Reliable Detection of Operational Performance Issues

For PV professionals, the early detection and diagnosis of faults is of the utmost importance to obtain and maintain high energy yield of PV systems. Moreover, the timely remediation of faults not only restores the production promptly but also avoids the occurrence of additional component failures and leads to reduction of costs for operation and maintenance (O&M). However, this early and reliable detection of issues requires accurate models of the expected behaviour of the well-performing PV plant. In practice, tools are required to help PV plant owners and operators reducing the occurrence of component failures and thus reducing O&M costs. Ideally, such models and tools can provide insight in the root causes of performance losses.

1.2. OBJECTIVES

The main goal of the *Performance Plus* project was to develop and demonstrate models and tools to monitor, control and test PV systems. These models and tools would then be used to optimize and enhance the performance, reliability and lifetime of commercial PV systems. Furthermore, the work focused on improved integration of PV-generated electricity into the power system through methods for short-term forecasting, testing and diagnostics, integrated energy management and storage control of thermal systems and PV system monitoring and control. The goal is to improve the competitiveness of PV on the system level.

The resulting collection of tools will be applicable to the decisive phases in the life cycle of a PV plant, namely, design, operation and maintenance. All results and models are validated with empirical data and the resulting tools are demonstrated in a relevant environment.

The project also tackled the question of energy storage. PV is increasingly becoming integrated with on-site storage and energy management systems. This is done in order to increase the sales value of the PV electricity for the owner or an aggregator acting as intermediary. Of course, it is essential for these systems to have a good control system. Suboptimal control may cause unnecessary over-sizing of storage devices or a significant drop of the overall energy conversion efficiency of the PV-energy management-storage system. Here, model-predictive control (MPC) is recommended for optimally controlling these systems.

2. The *Performance Plus* Project

2

The Performance Plus Project

2.1. MAIN OBJECTIVES

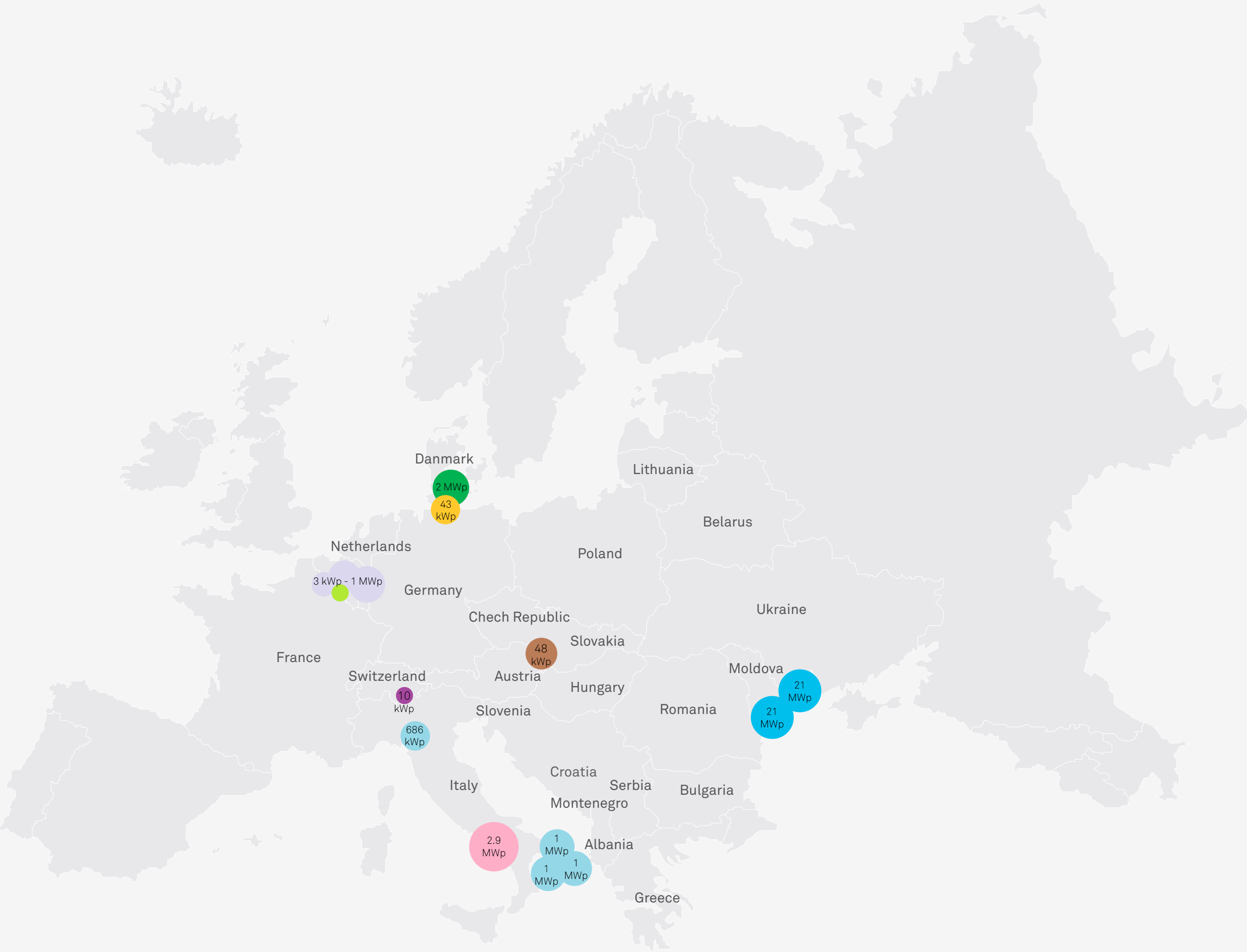
The *Performance Plus* project focused on reliable, cost-effective and highly performing photovoltaic systems. The overall objective of *Performance Plus* was to develop and demonstrate models and tools for monitoring, control and testing of PV systems. Means for a better integration of PV-generated electricity into the power system were provided by methods for short-term forecasting, PV system monitoring and integrated energy management and storage control.

The *Performance Plus* consortium looked at how to improve the PV system as a whole rather than on component level. Therefore, the PV modules and inverters were studied with focus on their operation within a system. Moreover, the *Performance Plus* project also studied the discrepancies between predicted and actual performance of PV systems. The consortium analyzed the way the uncertainties of all input parameters propagate throughout the PV modelling chain and affect the predicted performance. The developed models, methods and tools, aiming at reducing these uncertainties, focus on the early and reliable detection of operational performance issues by providing insight on the root causes of performance losses. This knowledge will help PV plant owners and operators to reduce the occurrence of component failures, and thus reduce their O&M costs. The developed models, methods and tools were validated and demonstrated within the project. The *Performance Plus* consortium had access to a total of 25 PV systems across Europe. Where needed, the monitoring data from these plants were integrated into 3E's monitoring and reporting platform SynaptiQ, so the developed methods and tools could be applied. Furthermore, a new type of irradiance sensor was developed within the project and prototypes were installed at five different sites across Europe for validation.

The main objective of the validation and demonstration phase was to bring the developed devices, methods and tools into practice and to ensure the quality of the results. The results of the long-term assessment of monitoring and control in view of sensing, fault detection, performance analysis, communication and effectiveness of the algorithms for energy management and storage control are presented in the public technical reports [10], [11]. The results of the validation and demonstration phase serve for transforming the project results into recommendations and applicable solutions for the industry.

2.2. AVAILABLE PV PLANTS FOR VALIDATION AND DEMONSTRATION

For the validation and demonstration of the models, methods and tools developed within the project, the *Performance Plus* consortium used monitoring data from a total of 25 PV systems across Europe. One of the installations has been in operation for more than 27 years; others have recently been installed with new PV technology. The available plants cover a wide range of installation capacity, from small residential-scale systems to large utility-scale PV plants, and are distributed over Europe as shown in Figure 1.



Consortium Members

- 3E
- SUPSI
- AIT

Users Group

- CEE
- Danfoss
- Geosol
- Oskomera
- SDU
- Platina

Figure 1 : Geographical distribution and size overview of the PV plants used for demonstration and validation activities

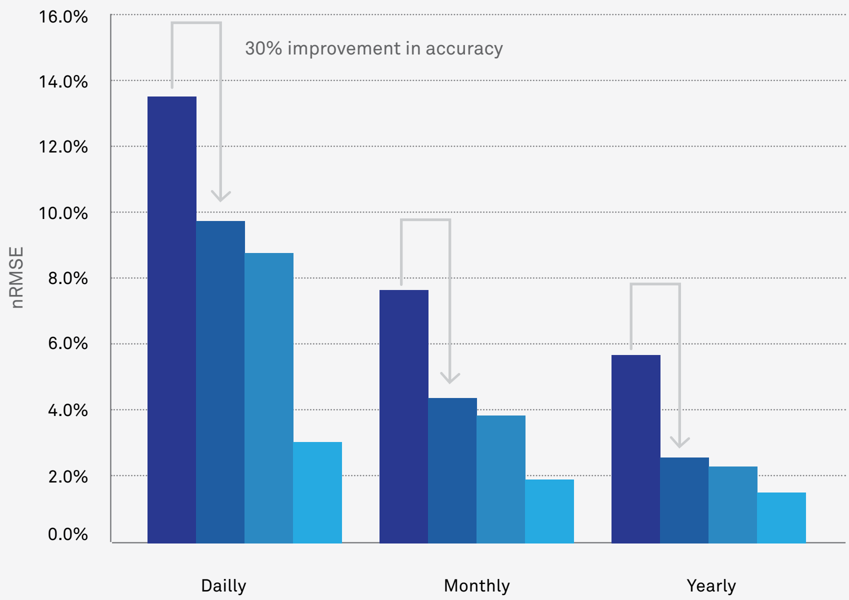
3. PV Plant Design

3

PV Plant Design

3.1. LONG-TERM RESOURCE ASSESSMENT

The assessment of solar resource is an essential part of photovoltaic plant design and operation. The quantification of uncertainty in the solar resource and the resulting PV energy yield is especially important for evaluating the financial risk of PV investments. Moreover, precise solar irradiance data is essential in order to produce robust PV energy yield predictions. The *Performance Plus* consortium has studied the way this uncertainty propagates throughout the PV modelling chain. The results of the analysis are documented in the public report *Best Practice Guide on Uncertainty in PV Modelling* [12]. The report shows that the errors in PV energy yield calculations are largely driven by the measurement and/or estimation of the solar resource. High-quality long-term ground-based measurements of solar irradiance are only available for very few places. Therefore, most professionals use long-term satellite derived irradiance estimates during the design phase of a PV plant. However, satellite irradiance estimates are subject to higher uncertainties. Methods to combine ground observations from meteorological stations and estimates from geostationary satellites are becoming more common. Within the *Performance Plus* project, a method that combines satellite estimates and ground measured data through a kriging-of-difference methodology has been developed [13]. The project validated its results with data collected over 204 sites across Belgium, the Netherlands and France. The results show that in average around 30% of improvement in accuracy can be achieved by this methodology. The results of these validations are shown in Figure 2.



- Satelitte derived dataset A
- Satelitte derived dataset B
- Combination of satellite derived data and ground measurements
- Pyranometer (secondary standard, well maintained and cleaned regurlary)

Figure 2 : Root mean square error of various satellite references compared with ground data from 204 weather stations in Belgium, The Netherlands and France and standard RMSE on pyranometer data

During the design phase of a PV plant, besides the uncertainties linked to the source of the data (i.e., pyranometer, silicon sensor or satellite estimates), the climate variability (i.e., year-to-year variability) has an important effect on PV energy yield calculations. Different sources of long-term solar irradiance are available worldwide. Moreover, these databases use irradiance data obtained by different methods and, sometimes, covering different periods. Given the long-term variations of irradiation, due to pollution and/or climate change for example, the time period used to estimate the irradiation for a typical year often has an important influence (10% and more). Therefore, the uncertainty is greatly depending on the source of data and the reference period used. Results presented in the *Best Practice Guide on Uncertainty in PV Modelling report* [12] show that when comparing yearly values of global horizontal irradiation (GHI) to the long-term average, this variability is mostly in the range of 4% to 6% for most places in Europe. However, these values can increase up to around 10% for mountainous regions.

Independent of whether the solar resource has been measured with a pyranometer, a silicon sensor or if it is derived from satellite estimates, the *Performance Plus* consortium recommends to always perform a quality control of the data and to properly assess and report the related uncertainties. If appropriate, ground measurements and satellite estimates should be combined by e.g. the methodology proposed in [13] in order to reduce the uncertainty of the solar resource assessment. This will help developers and investors to evaluate more carefully the financial risks during the design phase of the PV plant.

3.2. PERFORMANCE

Industry professionals use different performance models to predict the amount of energy that a PV system can produce. These models can differ significantly in their underlying mathematical formulations, approach and in the amount of data (assumptions) required for the simulation. The *Performance Plus* project provides recommendations for the performance assessment of the two main subsystems of a PV system, i.e., the PV array and the PV inverter.

3.2.1. PV ARRAY

Traditionally, the expected performance of a PV module or group of modules (PV array) is modelled based on datasheet parameters, laboratory tests and system configuration details using a bottom-up approach [14]–[17]. However, as shown, e.g., in [18], the predicted performance from these models can differ significantly among each other and from the real observed performance in the field. One of the main goals of the *Performance Plus* project is to better understand the discrepancies between the predicted and the real performance.

Several state-of-the-art PV module models (e.g. [19]–[24]) often cover only steady-state losses. Losses due to fast changing (unsteady) ambient conditions and/or non-uniform illumination (e.g., due to shadowing or soiling effects) are not addressed by these models. Field measurements and indoor wind tunnel experiments on PV systems show that significant inter-module and intra-module temperature differences exist [25]. Therefore, most of the current state-of-the-art PV module models are subject to errors when pushed beyond ideal conditions, i.e., when the PV modules are installed under non-ideal positions with highly variable ambient conditions. These models are therefore not appropriate for what-if explorations that extend potentially far beyond the available measured instantiations.

Figure 3 highlights unexplored territory in the state-of-the-art PV module modelling. The *Performance Plus* consortium has studied the effect of non-uniform illumination and fast changing ambient conditions. The project team has developed a white-box PV module model that combines the best of the different modelling types by incorporating optical, thermal and electrical aspects and by being suitable for simulating fast changing conditions and non-uniform illumination conditions [2]–[5].

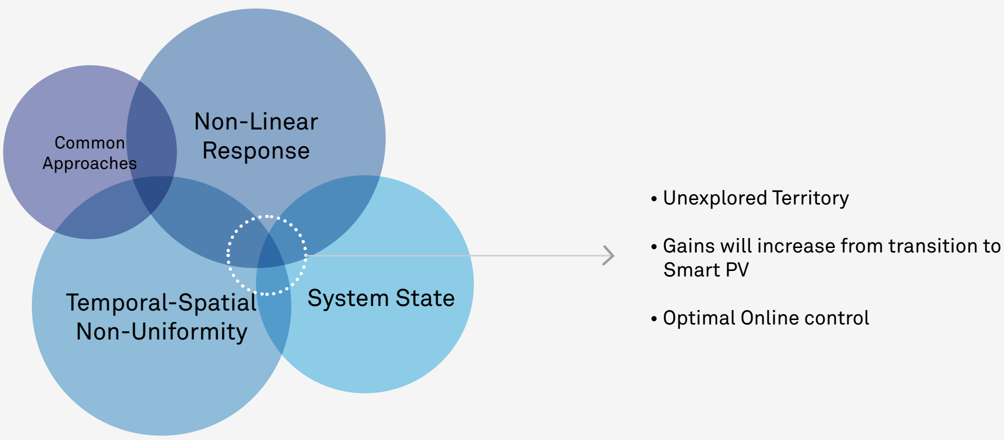


Figure 3 : The unexplored territory in actual pv module performance modelling, a combination of fast changing conditions and non-uniform illumination conditions with a long thermal state

The consortium validated this model using one second resolution data from an open rack module installed on a flat roof at the University of Oldenburg. The validation period covers more than one year, starting from the spring of 2014. Results of the validation show that under non-steady-state and non-uniform conditions, the developed model has higher accuracy than traditional models when calculating the PV energy output. The first validation results show that, e.g., for April 2014 the model predicted the hourly energy yield with an improved normalized root mean squared error (*nRMSE*) of 3.5% compared to 7.15% for the common practice simulation tool PVsyst. The validation results show that (especially for winter months) the proposed model retains its accuracy, whereas the average error of PVsyst increases considerably. Results of this first validation are reported in [5]. Moreover, the developed model is suitable for what-if explorations. This will allow PV plant developers to assess more efficiently the impact of different design choices, including various module topologies and different ambient conditions, amongst others.

For situations where a high accuracy of the power generation of a PV array is required in space and time, the *Performance Plus* consortium recommends the use of thermo-electric models as described in [2]–[5]. This is necessary, for example, when designing new types of PV modules or when optimizing the switching and maximum power point tracking (MPPT) of module integrated power converters or switches. The consortium has integrated this PV module model with a detailed circuit-level PV inverter model allowing fine-grain transient simulations. Experiments with local module-level inverters coupled to a PV module have shown that the thermal aspects are not negligible. Therefore, the temperature evolution of the PV cells in the module has to be coupled to the temperature impact of the inverter.

3.2.2. PV INVERTER

The PV inverter plays a key role in the power conversion chain of the PV system and thus directly influences the overall yield of the system. Any losses and malfunctions of the PV inverter have a direct impact on the whole PV system and may considerably reduce its energy yield.

For an accurate estimation of the overall performance of a PV system, the close-to-reality characterization of the PV inverter performance is essential. The *Performance Plus* consortium has developed a set of procedures to measure and characterize the performance of PV inverters in a holistic manner. These procedures use well established methods based on national and international standards (e.g., [26], [27]) and provide new procedures which were developed in the frame of the project. These test procedures and specification of tools for inverter performance in different conditions are documented in [6].

In a nutshell, the following tests are part of the recommended procedures:

- Verification of the DC input and AC output characteristics:
  Measurement of the conversion efficiency characteristic and its dependency on the DC input voltage and DC input power, the ambient temperature, and grid conditions;

- Measurement of the MPPT performance under steady state and dynamic array and irradiance conditions as well as non-uniform irradiance conditions (i.e., partial shading);

- Measurement of the self-consumption of the inverter and auxiliary systems;

- Measurement of the response of the inverter to control signals from plant controller and/or distribution grid operator;

The procedures aim at characterizing the electrical performance of the PV inverter, including the influence of various electrical parameters on the performance as well as identifying limitations of the PV inverter's operational area and their dependency on external factors. Additional tests are recommended by the *Performance Plus* consortium to characterize the performance related impact of the PV inverter on the performance of the PV array due to, e.g., a non-ideal MPPT. It is important to separate these performance aspects, which depend fundamentally on the characteristics of the PV array, string configuration etc., from the electrical characteristics, which are typically independent of the PV array.

By using the measured parameters obtained during these tests, a close-to-reality simulation of the PV inverter can be realized. Besides allowing the identification of potential issues during the PV plant design phase, this allows the recognition of degradation and aging issues during operational phase by continuously comparing the measured performance of the PV inverter with the initial characteristics.

3.3. RELIABILITY & LIFETIME

3.3.1. PV ARRAY

By today's standards, PV modules are expected to work for at least 25 years without any replacement, taking into account the projected lifetime of a PV plant. As shown in [7], PV modules can work for more than 25 years without being replaced. However, PV modules are affected by different degradation mechanisms throughout their lifetime. The degradation behaviour of a PV module already starts during the product design and production phase. During this phase, where all the raw materials, components, assembly and production technology are selected, the future degradation condition of the PV module is defined.
The *Performance Plus* consortium has studied the degradation mechanisms and modes of a PV module according to the single diode model. The results of this study are presented in the public report [7]. The research concentrated on determining the effects of degradation on the parameters required for thermo-electric PV module models, i.e., the short circuit current (I_{sc}), the open circuit voltage (V_{oc}), the series resistance (R_s) and the shunt resistances (R_{sh}). Furthermore, the possible time dependence for each degradation mode has been determined. The proposed flow for the performance prediction of a PV system is shown in Figure 4.

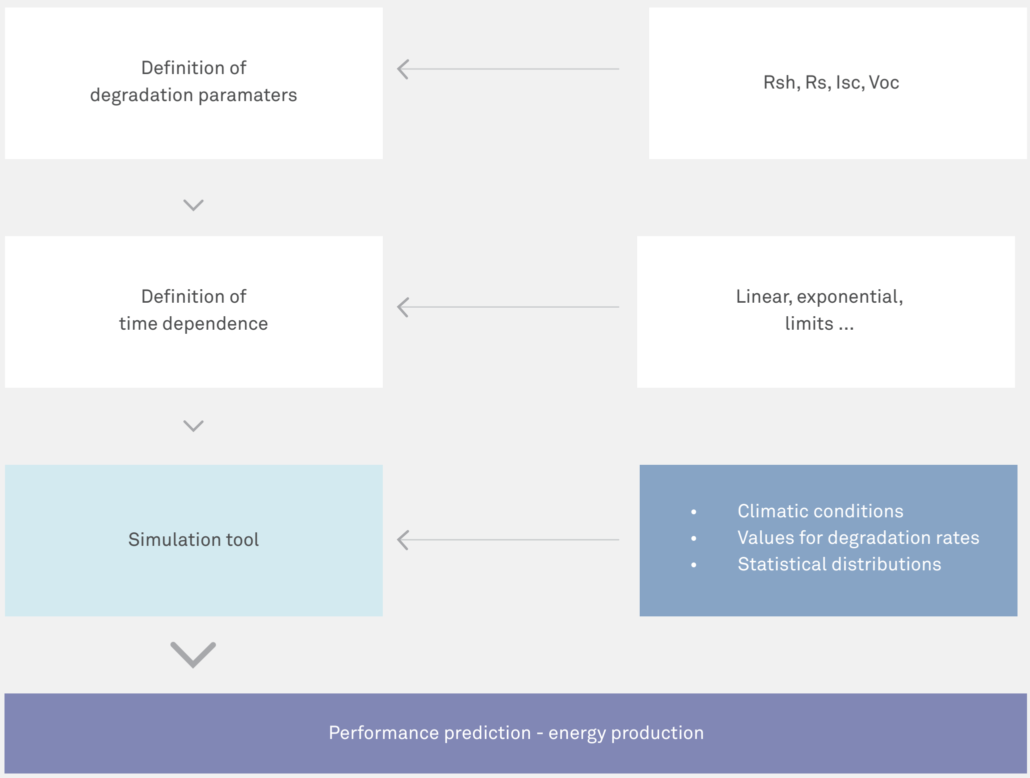


Figure 4 : Proposed flow for the performance prediction of a pv system

International standards such as the IEC61215 and IEC61646 norms for c-Si and thin-film modules respectively, provide testing procedures for PV module qualifications. These standards focus on the design qualification and, therefore imply climatic and mechanical testing. The IEC standard test procedures focusing on damp heat and thermal cycling could provide some information on the degradation mechanisms and the magnitude of the degradation rate of a specific PV module. However, the IEC standard qualification and test procedures were only developed for the approval of PV modules (pass/fail criteria after a defined time exposure) to ensure a safe operation over 25 years. These tests therefore are not suitable to determine the tendency of performance degradation during the PV module's lifetime.

Within the *Performance Plus* project, new indoor test procedures for degradation mechanisms were proposed. These new test procedures, still under development in the IEC working groups, are described in [7]. Within the new indoor test procedures, potential induced degradation (PID) tests and dynamical load testing are proposed. Both new test procedures are briefly described below.

The technical specification IEC62804 TS is being developed to determine whether a PV module design and the combination of materials used are PID sensitive. This test procedure consists of exposing the module under positive and negative system voltage – usually 1000 V – at a relative humidity of 85% and at a temperature of 60°C for 96 hours. The power degradation of the module is measured after the test and the module degradation is made visible by electroluminescence photography. The PID is correlated mainly to the degradation of the shunt resistance (R_{sh}), but also to the series resistance (R_s) and, therefore, to the loss of performance over the lifetime. Today, the correlation between the infield degradation and the indoor PID degradation is not clear and, therefore it is subject of further investigations.

The dynamic load testing defined in the IEC62782 draft specification provides a method to determine how well a PV module performs under dynamic load stress. This standard specifies that the module mounted as described by the manufacturer is submitted to 1000 cycles with a cycle time of 20 to 60 sec and a force of ± 1000 Pa. The test should give indication about the performance losses caused by interconnection and bonding defects as well as the sensitivity to cell cracking. Furthermore, the performance losses can be measured if thermal cycling tests are performed after the dynamic load tests.

Different case studies with PV modules operating in the field for long periods of time were analyzed by the consortium. The complete results of the analysis are presented in [7].

3.3.2. PV INVERTER

The reliability and lifetime expectancy of PV inverters as key components of PV systems are of utmost importance for further deployment of PV systems. Due to the technical complexity of today's PV inverters, their life time expectancy is limited compared to conventional electrical energy systems.

Actually, PV inverter reliability assessments are performed on component level, either during development or post-development phase. This current practice results in a gap whereby a unified PV inverter reliability and lifetime assessment test procedures is applied to the entire PV inverter. In order to overcome this gap, the *Performance Plus* consortium has developed a specific set of test procedures intended for PV inverter lifetime performance evaluation, applicable to all types of PV inverters available on the market [8]. These can then be applied for prototype testing by the manufacturer as well as by 3rd party labs for independent qualification testing.

These procedures are based on accelerated stress reliability testing methods which are custom tailored for PV applications. The test procedures are applicable to the entire PV inverter, applying a black box testing approach. For this purpose, the inverter is exposed to simulated marginal real life conditions, while the test stress frequency is increased with the intention to uncover PV inverter weaknesses, faults and failure modes. The recommended tests for the comprehensive assessment of the reliability of a PV inverter are summarized in Table 1.

Table 1 : recommended PV inverter lifetime performance evaluation tests

TEST	DESCRIPTION
Cold (Continental) Humidity Test	Evaluation of environmental conditions found during late fall, winter and early spring time in the continental climates
Hot (Tropical) Humidity Test	Evaluation of environmental conditions found in the tropical climates
Cold Soak Start Test	Evaluation of environmental conditions found in winter time or high elevation at night time when the PV inverter is turned off and subject to extreme cold
Desert Hot with High Solar Radiation Test	Evaluation of environmental conditions found in the hot and dry deserts with high level of solar insolation worldwide to determine influence of hot ambient temperature combined with thermal radiation inflicted on the PV inverter under test
Conductive Dust & Water Ingress Test	Evaluation of PV inverter performance under environmental conditions during rain and sand storms
Snow Drift Test	Evaluation of PV inverter performance under environmental conditions during a snow storm
Salt & Fog Test	Evaluation of PV inverter performance under environmental conditions in near proximity of sea and ocean shores

During each test described in Table 1, PV inverter measurements and derived measured quantities are monitored. In addition, each unit under test is being assessed individually for signs of potential issues that may lead to degradation of performance or reduction of life time. The tests allow to qualify the inverter design for a real world application under different climate conditions. Furthermore, the measured parameters, which are obtained during the tests, can be used for a close-to-reality assessment of the lifetime expectancy of the device.

3.4. COSTS AND REVENUES

During the last few years, the PV industry has made large technological progress on individual PV system components resulting in higher efficiencies and reliability at lower costs. However, the integration of these components inside the PV system is not always optimal, especially under real (non-ideal) operating conditions, leaving significant further potential for cost-reduction. In reality, PV system operating conditions are often non-ideal, as introduced in Section 3.2.1. The non-ideal operation of some individual components often has undesired effects on other components within the PV system. This does not only result in lower energy yield but also leads to flawed conclusions on the optimal system design.

The *Performance Plus* consortium has developed a PV system and financial optimization tool where the levelized cost of energy (LCOE) is calculated using the combination of the different PV models developed within the project. The tool and its validation are described in [9]. The consortium has validated the tool by analyzing different use cases. For each use case, a sensitivity analysis of different design options gave an indication of the reduction potential of the LCOE. Results show that a cost-efficient integration of the different PV system components is reached through holistic cost optimization. Moreover, the validation of the tool shows that the output results are very close to the real output of operating systems. The model was validated using real data from operational systems, measured at 15 minutes resolution. The resulting accuracy measures calculated at 15 minutes level are 0.5% and 12.4% of normalized mean bias error (*nMBE*) and normalized mean absolute error (*nMAE*) respectively. Results of this first validation are reported in [9].

3.5. LESSONS LEARNED

In addition to the recommendations presented in the previous sections, the *Performance Plus* consortium has formulated the following observations with regard to the design phase of a PV plant from the implementation of the project. Other stakeholders are encouraged to review them and build on the experience of *Performance Plus*.

- The development of advanced thermo-electric models requires high quality and high resolution data (one second measurements). Within the *Performance Plus* project, a dataset with these characteristics has been generated by the *University of Oldenburg*. Data sets of solar irradiance components (global, direct, diffuse, tilted and spectral), PV production, module temperature and sky images as well as meteorological standard measurements were recorded and archived for more than one year with a sample rate of 1 Hz. Sky images were taken every 10 seconds to derive total cloud cover, cloud type and cloud motion vectors for forecasting. The generated data can contribute to, among others, the further development and validation of advanced thermo-electric PV module models, new forecasting techniques, characterization of fluctuating irradiance and its impact on PV energy production, grid operation and power trading.

- Current IEC standard qualification and test procedures for PV modules such as the IEC61215 and IEC61646 norms were developed to ensure a safe operation over 25 years. However, these tests do not determine the tendency of performance degradation during the PV module's lifetime. The new indoor test procedures for degradation mechanisms proposed within the project [7], which are still under development within IEC wor king groups, will allow to determine the tendency of performance degradation mechanisms caused by potential induced degradation (PID) and dynamic load stress during the PV modules lifetime.

- Due to its complexity, present-day PV inverters' lifetime expectancy is limited compared to conventional electrical energy systems. Furthermore, the state-of-the-art PV inverter reliability testing methods are performed on component level resulting in a lack of unified PV inverter test procedures applied to the entire PV inverter. The proposed holistic test procedures for PV inverter characterization and lifetime performance evaluation help overcome this limitation, contributing to the increased reliability and lifetime expectancy of PV inverters.

3.6. TAKEAWAYS

The assessment of the solar resource has been identified as the most important element in the contribution to the total uncertainty;
The *Performance Plus* consortium recommends to always perform a quality control of the measured/estimated irradiance data and to properly assess and report the related uncertainties;
If appropriate, ground measurements and satellite estimates should be combined as described in [1] in order to reduce the uncertainty of the solar resource assessment;
For situations where a high accuracy of the power generation of a PV array is required in space and time (e.g., for module-level inverter applications), the use of fine-grain thermo-electric models as described in [2]–[5] is recommended;
Fine-grain transient models for the PV micro-inverter should be integrated in the PV module model to reach the fully achievable accuracy;
By using the measured parameters obtained during the inverter test procedures recommended by the consortium in [6], potential issues during the PV plant design phase as well as degradation and aging issues during operational phase can be identified;
The new indoor test procedures proposed by the consortium in [7] will allow to determine the tendency of performance degradation mechanisms caused by PID and dynamic load stress during the PV modules lifetime;
The specific set of test procedures intended for PV inverter lifetime performance evaluation described in [8] allow to qualify the inverter design for a real world application under different climate conditions;
The lifetime expectancy of PV inverters can be assessed by using the measured parameters obtained during the tests described in [8];
Cost-efficient integration of the different PV system components can be reached through a holistic cost optimization approach by using a tool that combines advanced PV models as described in [9].

4. PV Plant Operation

4

PV Plant Operation

4. PV PLANT OPERATION

Figure 5 illustrates the full energy conversion chain of a generic PV plant according to [28], and the different parameters to be measured in real time by a monitoring system. Not all components of 5 are present in most cases. In reality, back-up sources, energy storage and load are missing in most large PV systems.

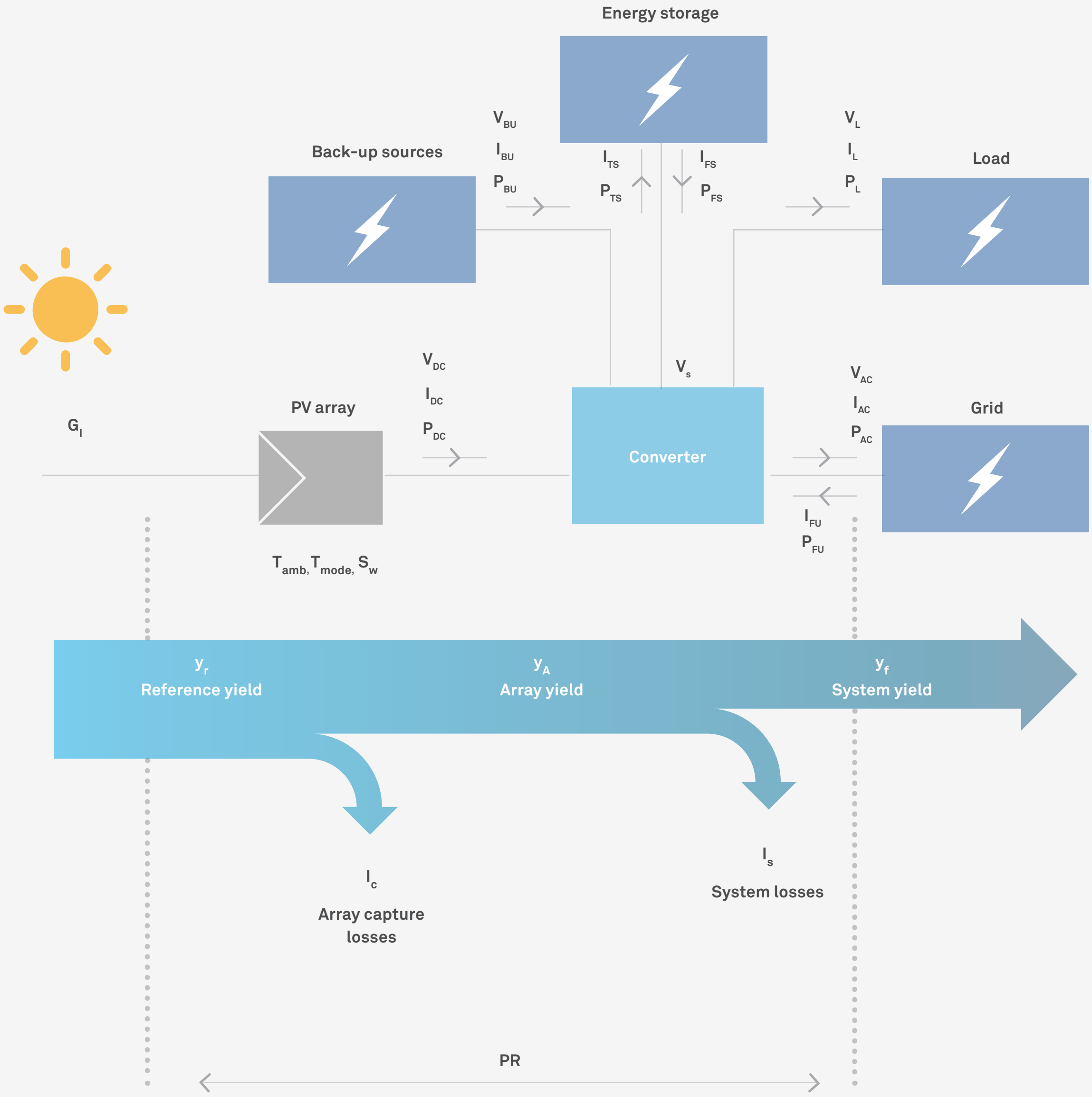


Figure 5 : Energy flow in a grid-connected PV system and parameters to be monitored

Guidelines for PV plant monitoring, including, among others, recommended accuracies for measurement devices and sampling intervals are detailed in the annex *Monitoring Guidelines* of the public report [12]. The sampling interval for parameters which vary directly with the irradiance should be at least one minute. Generally all parameters should be sampled every minute, except for the ambient temperature which may be sampled at lower rates. In most monitoring systems, the sampled data is then averaged over a recording period of 5 or 15 minutes. The shorter the monitoring period is, the more advanced the monitoring intelligence will be.

4.1. OPERATIONAL RESOURCE ASSESSMENT

4.1.1. SOURCES & SENSORS FOR MONITORING

The quantification of the solar resource during PV plant operation is essential as it allows to calculate PV performance indicators like, e.g., performance ratio (PR), energy performance indices (EPIs), etc. This is particularly important since it enables plant operators not only to monitor but also to improve the operational performance of the PV plants during their lifetime. However as mentioned in Section 3.1, the accuracy on irradiance quantification is today the most important factor impacting the accurate determination of the system performance.

The *Performance Plus* consortium has studied how the uncertainty on the solar resource quantification is propagated through a monitoring system and impacts the calculated PV performance indicators. The results of the analysis are documented in [12]. The report shows that, e.g., the uncertainty in yearly PR calculations is typically between ± 2.5% and ± 3% for a good monitoring system. By this we mean a properly calibrated and maintained system with a dedicated energy meter and a secondary standard pyranometer on site measuring the plane-of-array (POA) irradiance. However, when using lower accuracy irradiance measurement devices (e.g. silicon sensors) or satellite derived estimates and only inverter readings, the uncertainty on the calculated PR can go up to ± 4% to ± 6%.

In addition, the dynamics of the environmental meteorological conditions play a big role. For example, in [29] it is shown that forecast accuracy for southern Spain (with a lot of sunny days) is higher than in Central Europe. Furthermore, the uncertainty increases when conventional coarse-grain measurement intervals of e.g., 15 minutes are used to predict over short forecast horizons (e.g. 30 or 60 minutes). This is further discussed in Section 5.1.

4.1.2. THE ESA SENSOR

The ESA sensor, developed within the *Performance Plus* project, is an innovative tool that significantly improves both the costs and the ease of operability in measurements of solar irradiance. The ESA sensor is a fixed detector of global, diffuse and direct solar irradiance. The irradiance is received by several photodiodes covering the upper hemisphere and allowing for directional measurements. The photodiodes are covered by a black hemispherical cap (dome). A built-in processor (microcontroller) transforms the raw measurements into global, diffuse and direct irradiance. Moreover, it also provides information about the sun position. The sensor uses the Modbus RS485 communication protocol, the most popular industrial protocol being used today, which makes it compatible with most of the data loggers available in the market.

PV plants equipped with solar tracking systems traditionally measure the solar resource with a single station that measures global, direct and diffuse irradiance. Such solar irradiance measurement stations are relatively expensive (around 15,000 € for a turn-key solution i.e., including data logger and installation work) and require qualified personnel for installation and maintenance. In contrast to such solar irradiance measurement stations, the ESA sensor features a single robust, small and portable device (5x5x5 cm, 0.3 kg) as shown in Figure 6. Furthermore, the low cost of the ESA sensor (around 2,000 € for a turn-key solution, i.e. including data logger and installation work), the very low energy use (0.2 W) and the simplicity in its installation, operation and maintenance make it a very attractive solution.

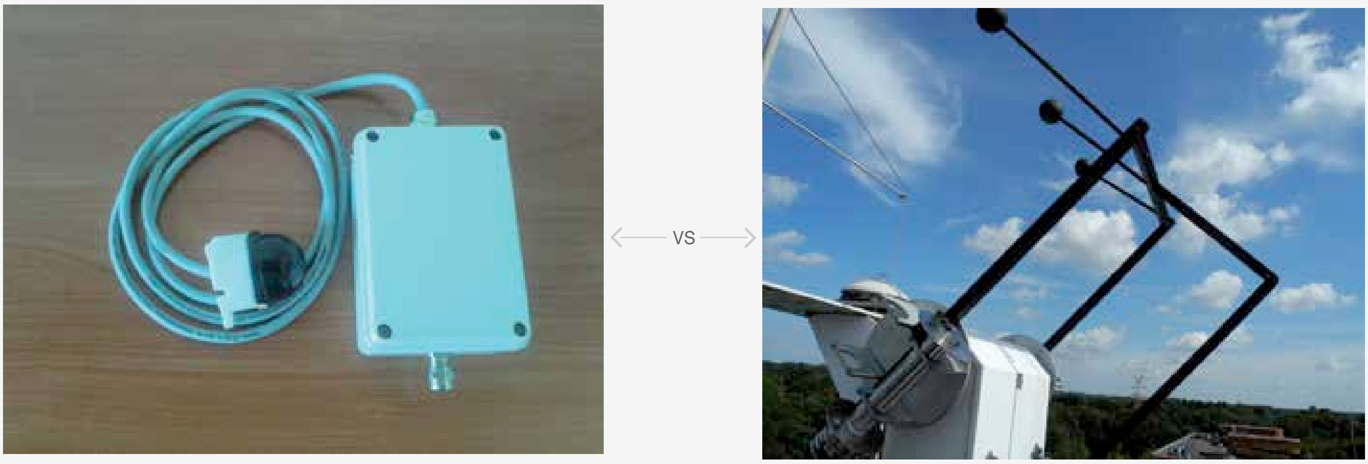


Figure 6 : Comparison of the ESA sensor with its junction box (left - source: Alitec Srl) and an equivalent solar irradiance measurement station equipped with a suntracker with shaded pyranometer and pyrheliometer that measure diffuse and direct normal irradiance (right – source: University of oldenburg)

The ESA sensor's innovative features result in reduced monitoring costs and maintenance efforts, thus allowing not only for small PV plants to perform solar irradiance monitoring, but also for medium to large PV plants to perform distributed rather than single-point monitoring. Moreover, in the field of energy management and optimal control of thermal systems, it enables the active optimization and fine-tuning of heating and/or cooling related energy use.

4.2. PERFORMANCE

The performance of a PV system is to a very high degree determined by the PV array characteristics. Accurate assessment of these characteristics is important for the accurate prediction of the PV power generation, for the reliable detection of malfunctions and for the evaluation of the health of a PV array in general. It is highly desirable that performance issues are detected early in order to facilitate pro-active maintenance practices, reducing downtime and increasing energetic performance, finally leading to increased electricity production.

4.2.1. INTELLIGENCE FOR OPERATIONAL MONITORING

Early detection and diagnosis of faults during PV plant operation are essential in order to obtain and maintain the energy yield high. Early remediation of faults not only restores generation promptly but also avoids the occurrence of additional component failures and leads to reduction of O&M costs. Early and reliable detection of performance issues requires an accurate model of the expected behaviour of the well-performing PV plant. As highlighted in previous sections, these models rely on accurate input parameters and, therefore accurate sources and sensors for monitoring are required to enable early detection and diagnosis of faults during PV plant operation.

The *Performance Plus* consortium has developed a methodology able to characterize the PV array through physical parameters estimated from operational data and to provide insight in the root causes of performance losses. This methodology has been called the PV *Health Scan* and is documented in [30]. The PV *Health Scan* methodology is illustrated in Figure 7. The method starts from closed-form relationships between regression parameters and underlying physical parameters. The methodology allows the systematic analysis of operational data in an efficient way, identifying how design choices and O&M practices lead to inferior or, on the contrary, superior performance in the field.

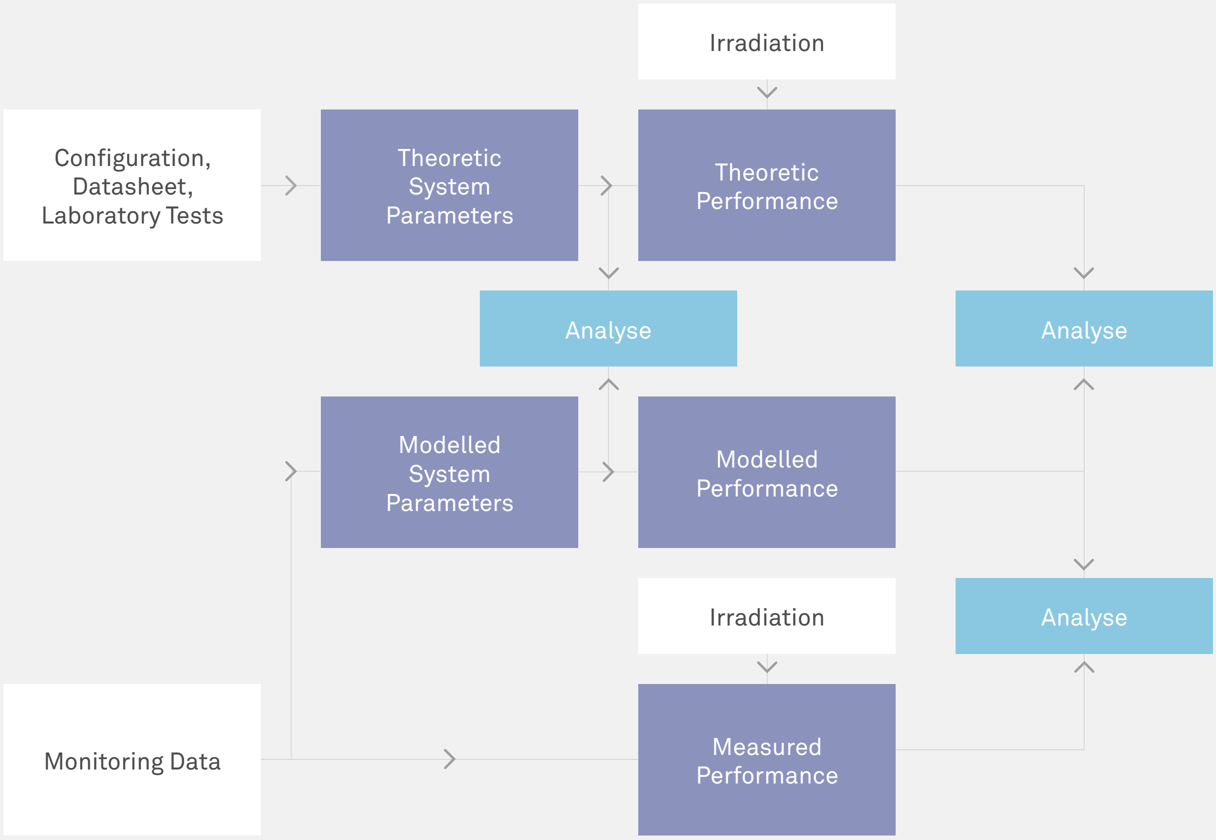


Figure 7 : PV *health scan* methodology

In a nutshell, the following steps are part of the PV Health Scan methodology:

- Define physical models of MPP voltage and current as a function of the environment;
- Train coefficients of physical models with operational data;
- Analyze differences between theoretical and trained model parameters;
- Analyze differences between measured, modelled and theoretical performance.

The PV *Health Scan* methodology has been validated and demonstrated using more than one year of operational data from several PV plants across Europe. Results of the validation and demonstration are presented in the public technical report *Demonstration and Validation Report for Sensor and Monitoring System* [10]. The application of the methodology during the validation and demonstration phase helped to identify several operational issues and design flaws. Amongst others, the following issues were identified: string failures, bypass diode failures, partial shading, potential induced degradation (PID) and unintentional power loss caused due to inverter sizing or incorrect inverter settings. Moreover, for some cases it was shown, thanks to the PV *Health Scan* methodology that solving these issues could increase the performance by 10% and more.

4.2.2. ON-SITE TESTING

Additional on-site inspections and tests may be needed in order to troubleshoot on possible root causes of performance affecting issues, complementing the results obtained through the PV *Health Scan* methodology. Once the portion of the PV system that is affected has been identified, different on-site tests can be performed. Amongst others, the measurement of *I-V* characteristics needs to be performed. To obtain an accurate measure of the *I-V* curve of the string, it is strongly recommended to do it under stable conditions, as measuring during cloudy conditions may cause significant errors. A first analysis of the comparison between the measured and the expected *I-V* parameters can already give a suggestion on the root cause of a problem. Furthermore, detailed analysis should be run to distinguish between possible degradation modes. The *Performance Plus* consortium developed a set of simple comparisons useful for on-site measurements. In addition, depending on situations, simple methods to discriminate between different phenomena that lead to similar effect on *I-V* shape were developed. These procedures and tools for PV system field testing are documented in [31] and are introduced in Section 4.3.2.

4.3. RELIABILITY & AVAILABILITY

4.3.1. DEFINITIONS

Reliability is the probability that a given component or product will perform in accordance with expectations for a predetermined period of time in a given environment. A low reliability leads to high O&M costs as well as low system availability. The availability of a PV plant is commonly calculated as a time-based indicator. The time-based availability represents the percentage of time during which the PV plant was producing and is expressed as the ratio between the duration of production activity and the recording period with sufficient irradiation for a minimal production.

While relatively easy to calculate, the drawback of this time-based indicator is that it does not allow for the calculation of the impact of unavailability on the overall system yield. Hereto, the *Performance Plus* consortium looked into an alternative availability indicator, namely the energy-based availability. The energy-based availability takes into account the reference yield and therefore indicates the energy lost during times of unavailability. The energy-based availability is calculated as the ratio between the reference yield that has been converted to electricity and the total reference yield.

In order to determine the impact of individual components on the overall system availability, the availability of individual components should be calculated. A properly designed monitoring system should be able to provide the data required to calculate these availabilities, thus allowing the operator to identify which components are under-performing and to prevent potential future unavailabilities.

4.3.2. TESTING AND DIAGNOSTICS

The *Performance Plus* consortium has developed a set of procedures and tools for PV system field testing to detect issues in PV plants affected by under performances. The developed methods, documented in [31], include tools to improve laboratory testing and tools for outdoor testing of PV plants.
The tools for laboratory testing focus on an improved PV modules sampling procedure with a clear definition of the number of PV modules to test, selection of modules and a final lot acceptance report. For the definition of number of modules to test, the consortium has developed a software called APOS which calculates the number of modules to be tested ensuring the defined statistical significance of the test results. Once the number of modules to be tested is determined, instead of randomly choosing the PV modules from the batch, the consortium has developed a tool to avoid erroneous selections. The developed tool creates clusters of the batch of the modules allowing a statistically significant sample of PV modules.
Furthermore, the procedures and tools for PV system field testing aim to detect different modes of degradation (PID, optical, electrical or mechanical damage), using traditional light *I-V* curve measurement and innovative dark *I-V* measurement techniques. Beyond these measurements, the consortium implemented numerical methods to extract parameters in order to differentiate between failures and degradation modes that can happen in operational PV plants.

Light *I-V* curve measurements are the basic tool to assess PV modules performance. During the measurement period, the environmental conditions need to be very stable. Furthermore, the obtained curve will be translated to standard test conditions (STC), i.e., an irradiance of 1000 W/m2, a temperature of 25°C and an air mass of 1.5. It is strongly recommended by the consortium to perform these measurements with high irradiation, i.e., at least 700 W/m2 and if possible with no extreme module temperature. The proposed procedure as support for the on-site measurements is presented in 8 and explained in detail in [31]. Furthermore, the importance of double checking the environmental sensors, as even very small mistakes can lead to wrong conclusions, is highlighted in Figure 8.

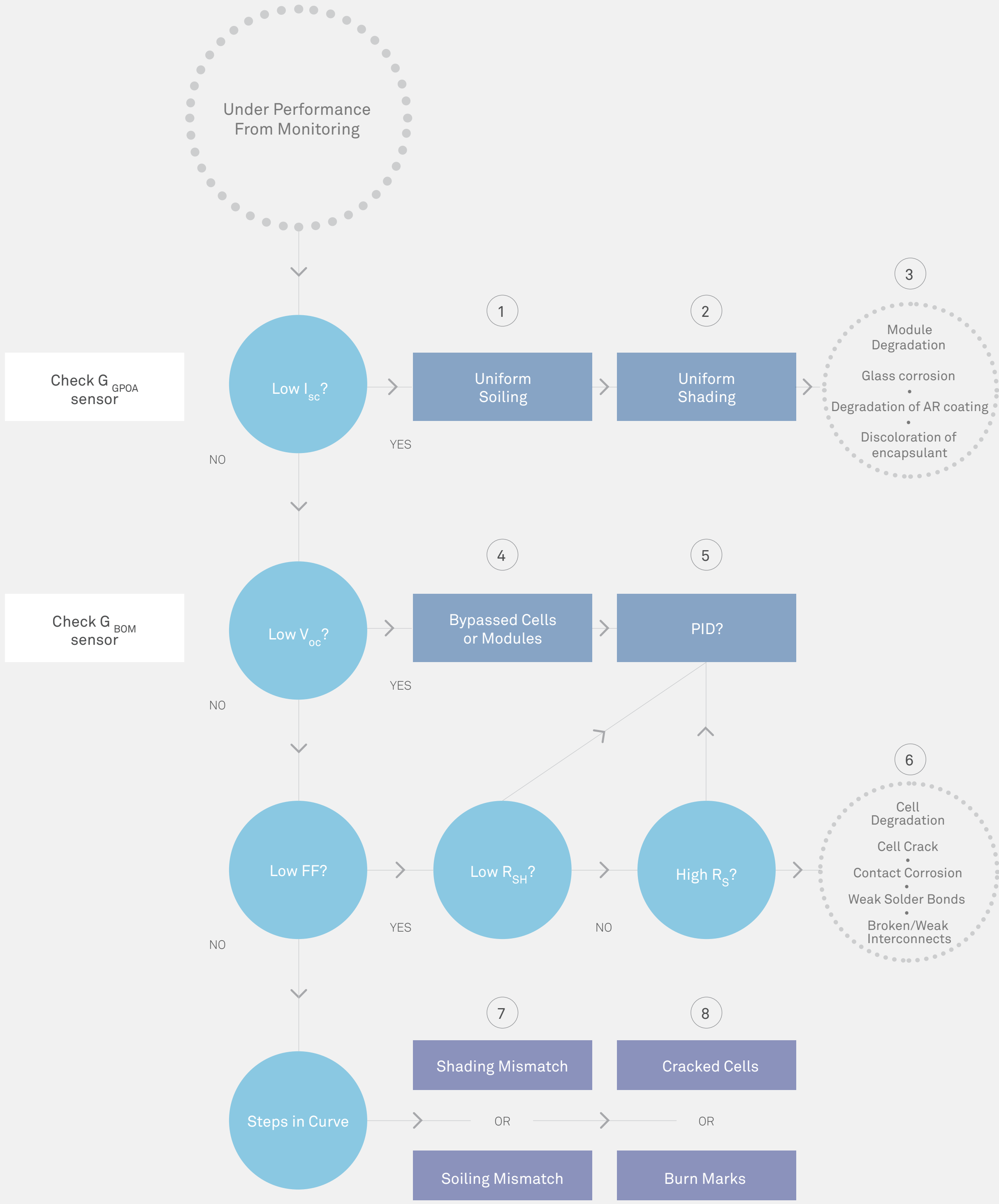


Figure 8 : Flow chart as a support for on-site PV modules measuring procedure

Dark *I-V* curve measurements are very accurate to evaluate the electrical parameters of PV cells and modules, and therefore are widely used in laboratories but rarely used on site. A dark *I-V* field measurement procedure has been developed within the project. Dark *I-V* measurements have clear advantages over the light *I-V* measurements for the following reasons:

- Not affected by optical factors (shading, soiling, transmittance and spectral response);
- Not affected by light intensity, homogeneity and spectrum;
- It does not require a fast measurement process;
- More temperature uniformity along the string.

The main disadvantage however, is that dark *I-V* curve measurements cannot provide information on optical performance of the module and therefore it should be coupled with light *I-V* measurements. In addition to the analysis at DC side (PV modules and string testing procedures), the consortium has developed a procedure for troubleshooting at PV inverter level. A flow chart for the proposed procedure for on-site PV inverter testing is presented in Figure 9 and explained in detail in [31].

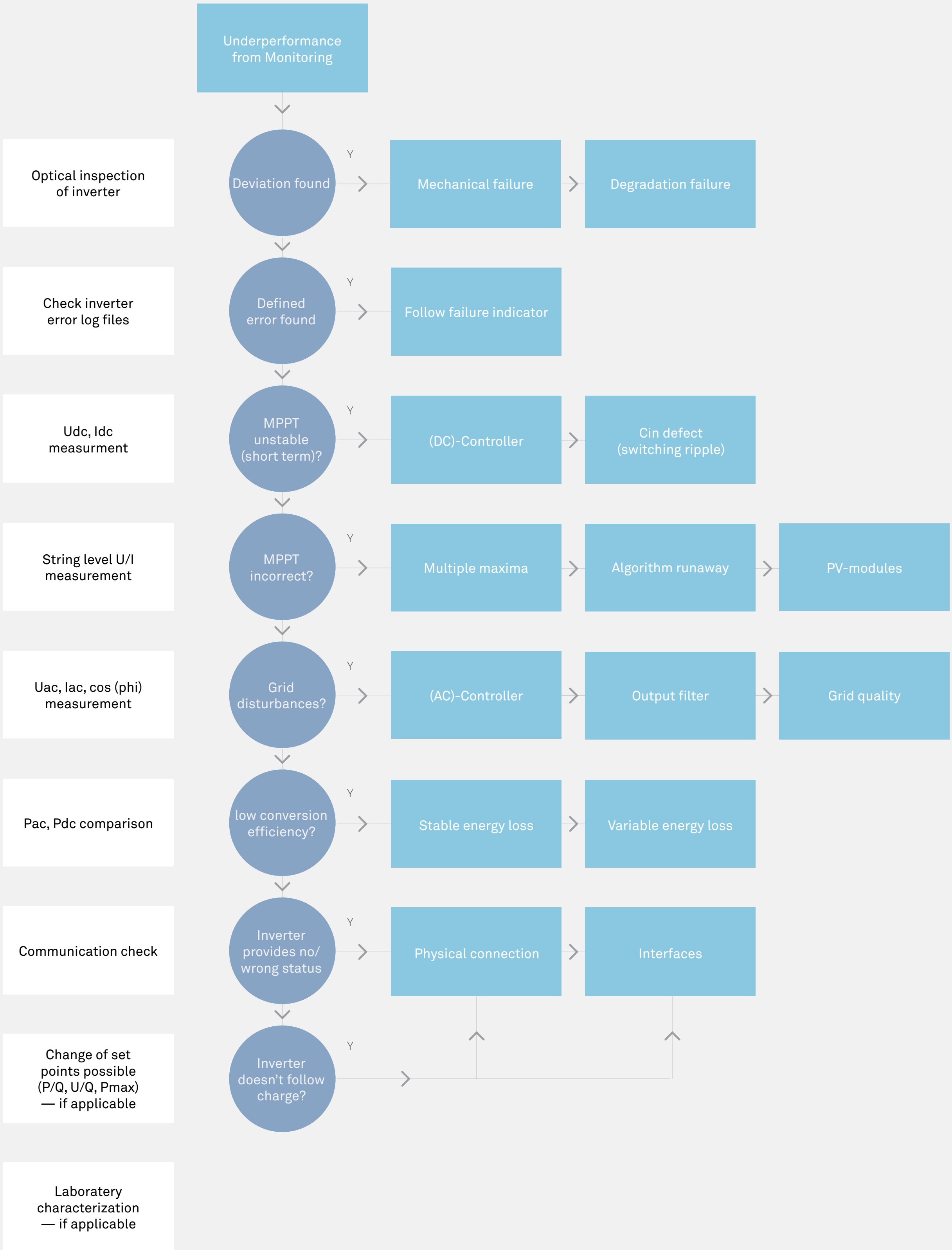


Figure 9 : Procedure for on-site inverter inspection

4.4. LESSONS LEARNED

In addition to the recommendations presented in the previous sections, the *Performance Plus* consortium has formulated the following observations with regard to the operational phase of a PV plant from the implementation of the project. Other stakeholders are encouraged to review them and build on the experience of *Performance Plus*.

- All sensors within a monitoring system (particularly irradiance sensors) should be regularly validated against independent reference sources (e.g., satellite derived datasets). Maintaining reliable measurements is crucial for implementing advanced monitoring intelligence and allow for the early and reliable detection of performance issues.

- When connecting a PV plant to a monitoring platform, special care must be taken with the entered configuration parameters, as faulty inputs can lead to false alarms and/or erroneous interpretation of results. Several batches of modules were tested within the project for lot acceptance. These tests were carried out in the accredited laboratory "Swiss PV Module Test Center" (SPVMTC) from SUPSI. Often the actual measurements differed significantly from the expected values. This could be due to, among others, erroneous calibration of manufacturer equipment or inadequate transportation of PV modules which caused cell cracks. The consortium has developed a new set of procedures for PV batch testing with a clear definition of number of PV modules to test, selection of modules and a final lot acceptance report.

- Despite the highlighted advantages of the dark *I-V* measurements compared with standard light *I-V* curve measurements, the main disadvantage is that dark *I-V* measurements cannot provide information on optical performance of the module and therefore, they should always be coupled with light *I-V* measurements.

4.5. TAKEAWAYS

In order to maximize PV plant yield and minimize O&M costs, the continuous monitoring of both actual power output and solar irradiance is crucial;
The costs and the ease of operability in measurements of solar irradiance components (i.e. direct normal and diffuse irradiance) are significantly improved by the developed ESA irradiance sensor compared with an equivalent solar irradiance measurement station;
The ESA sensor allows not only for small PV plants to perform solar irradiance monitoring, but also for medium to large PV plants to perform distributed rather than single-point monitoring;
In the field of energy management and optimal control of thermal systems, the ESA sensor improves the forecasting and control of heating and/or cooling related energy use;
The PV *Health Scan* enables the automatic identification of root causes affecting the performance of a PV system promptly. The methodology allows identifying how design choices and O&M practices lead to inferior or, on the contrary, superior performance in the field;
For some cases it was shown, thanks to the PV *Health Scan* methodology that solving the identified issues could increase the performance of the PV plant by 10% and more;
The new developed procedures and tools will help to improve laboratory testing and to detect issues in PV plants affected by under performances;
The proposed dark *I-V* curve field measurements should be coupled with the traditional light *I-V* curve measurements. The advantages include, among others, more uniform temperature along the string, no need for fast measurement process, the measurements are not affected by light intensity, homogeneity, spectrum and by optical factors such as shading, soiling, transmittance and spectral response.

5. Energy Management And Control

5

Energy Management and Control

Optimal energy management of a PV plant goes beyond maximizing the output of a single PV array. A system level optimization is required to achieve an optimal energy management. By considering an electricity-consuming load and an energy storage system, the PV plant behaves as a system, the output of which can be controlled to minimize the losses or to minimize the overall system cost.

Accurate meteorological and PV output forecasting models are required to perform an overall optimization of the system operation.

5.1. SOLAR RESOURCE AND POWER FORECASTING

5.1.1. METEOROLOGICAL FORECASTING

Accurate yield forecasts for the coming minutes, hours and days (Figure 10) are required by power producers, grid operators and power traders. The energy yield of a PV system is largely determined by the solar resource. As shown in [12], the most important element in the contribution to the total combined uncertainty in energy yield calculations is the measurement and/or estimation of the solar resource. In addition to fluctuations in the solar resource caused by the changing position of the sun, clouds and aerosols have a significant influence on the solar radiation intensity and thus on the resulting energy yield of a PV system.

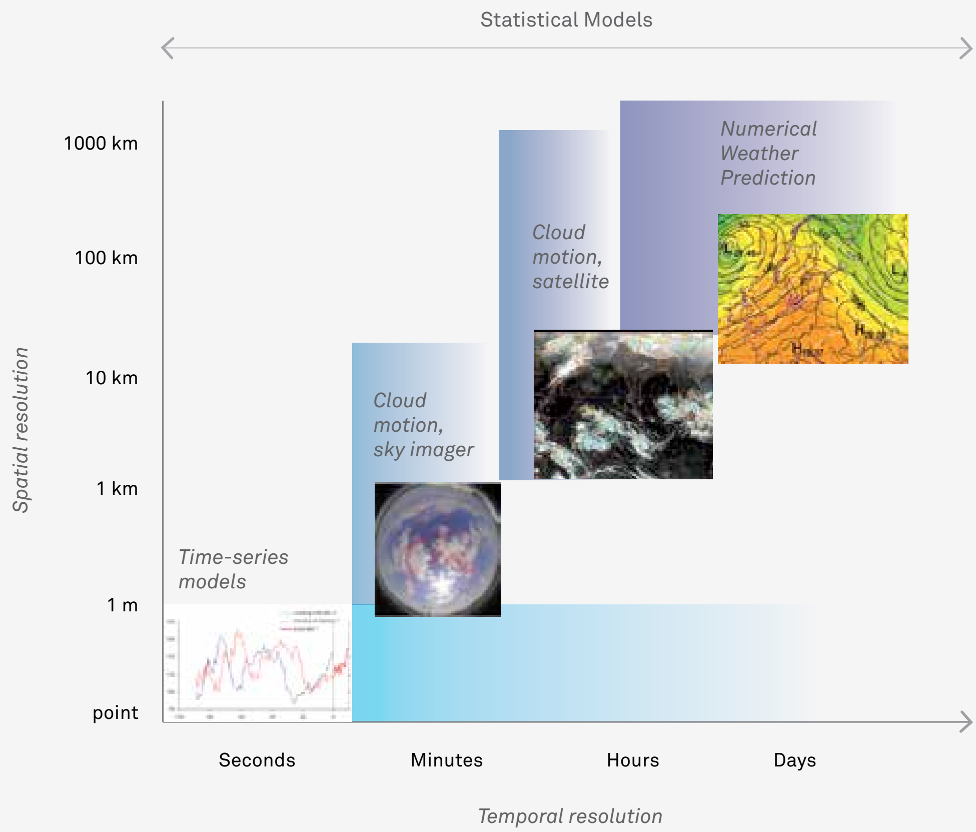


Figure 10: Spatial and temporal resolution of different model approaches for forecasting solar irradiance

Clouds and aerosols have a high spatial and temporal variability. They require different data sources and models in order to achieve optimal forecasts of the cloud cover, transmission characteristics and the resulting surface solar irradiance. Information on the global solar irradiance is required for PV systems and therefore, mainly optically thick clouds are of interest for this application. Concentrating solar power systems on the other hand, only utilize direct solar irradiance which means that optically thin cirrus clouds and aerosols also have to be accurately forecasted.

Different model approaches for forecasting solar irradiance covering different spatial and temporal resolutions are available in the market (Figure 10). Statistical time-series models are suited for very short temporal resolutions and site-specific forecasts. Images from ground-based sky cameras enable high-resolution, spatial forecasts with a time horizon of up to 20 minutes. Satellite based data allows forecasts ranging from the next 15 minutes to several hours with a spatial resolution of up to several kilometres. Numerical weather models enable forecasts of up to several days in advance with a resolution of 3 to 10 kilometres (local and regional models) with hourly increments. Global models have coarser resolutions.

The *Performance Plus* consortium focused on irradiance forecasting using sky imagery [32]. Images from ground-based sky cameras enable a detailed analysis of the cloud distribution and their motion vectors. A machine learning approach for retrieving direct and diffuse irradiance from sky images has been proposed within the project [33]. One year of measurements at the University of Oldenburg was used as a robust data basis for the proposed approach. The measured data sets consist of direct, diffuse and global horizontal irradiance measured with a sample rate of 1 Hz (i.e., 1 second resolution). Hemispheric images were taken every 10 seconds by a sky imager mounted close to the radiometers.

Results of the validation show that the global horizontal irradiance (GHI) retrieved on the basis of sky images and a machine learning approach, outperforms Meteosat Second Generation (MSG) satellite derived data (HELIOSAT-method [34]) for the measurement site of the University of Oldenburg. The overall results of the validation show that sky image analysis provides very high resolution binary cloud masks, but has limitations in deriving aerosol and cloud optical properties. However, as no expensive radiometric measurement devices are required, the proposed approach reduces significantly the initial investment and operational costs.

Moreover, the *Performance Plus* consortium investigated the combination of the different forecast models to reduce further the forecast error. The combination of different forecast models has the potential for improving forecast accuracy by simple averaging, exploiting that forecast errors of different models are usually only partly correlated. In addition, combination methods based on statistical analysis are proposed for an optimum weighing of the forecast models in dependence on the weather situation or the forecast horizon.

Conversion to the Plane of the Array

The forecasted GHI has to be converted to the plane-of-array (POA) in order to, e.g., forecast the PV power output. The conversion of the GHI to the POA irradiance requires two major steps: first the GHI is split into its components, i.e., horizontal diffuse irradiance and horizontal direct irradiance, by the use of a decomposition model; subsequently the diffuse, direct and ground reflected irradiance components are transformed to the POA and recombined again in order to obtain the global irradiance in the POA.

Different combinations of decomposition methods and algorithms for the horizontal to the POA conversion were evaluated by the *Performance Plus* consortium. The results of the validation using more than two years of five minutes data measurements from two secondary standard pyranometers at a site in France are presented in [12]. Results from the validation show that even when using the best combination of algorithms, a normalized root mean squared error (*nRMSE*) of 4.8% was obtained when comparing the converted irradiance to the POA and the pyranometer measurements. This uncertainty is propagated through the models when e.g., forecasting the PV power output and therefore has to be properly quantified and accounted for as recommended in [12].

5.1.2. PV POWER OUTPUT FORECASTING

Most of the state-of-the-art PV power output forecasting products focus on long-term horizon periods and work with relatively low resolution data (i.e. hourly resolution). While they require rather simple techniques allowing reasonable accuracy, these models are not suited for short-term horizon periods and especially under highly variable conditions. The fluctuating nature of the solar resource (as shown in the previous section) highlights the need of a suitable PV module model for calculating the PV energy yield of a PV system under such non-standard and non-ideal conditions.

Within the *Performance Plus* project, a PV module model that is suitable for simulating non-steady-state and non-uniform illumination conditions has been developed ([2]–[5]) and has been introduced in Section 3.2.1. However, the relatively low execution speed of this model would not allow it to be used for on-line forecasting or nowcasting purposes. Therefore, the *Performance Plus* consortium has studied different techniques to significantly speed up the computation without compromising the accuracy. This has been achieved by a combination of a one-time a priori scenario clustering phase and a continuously executed scenario detection phase during operation. The first results of this new approach are presented in [35] and summarized in Figure 11. The results show that this approach is more suitable than the state-of-the-art methods, especially under highly variable weather conditions and for short forecasting windows where the neural networks would have to be re-trained for a long time period to obtain the most accurate results shown in Figure 11.

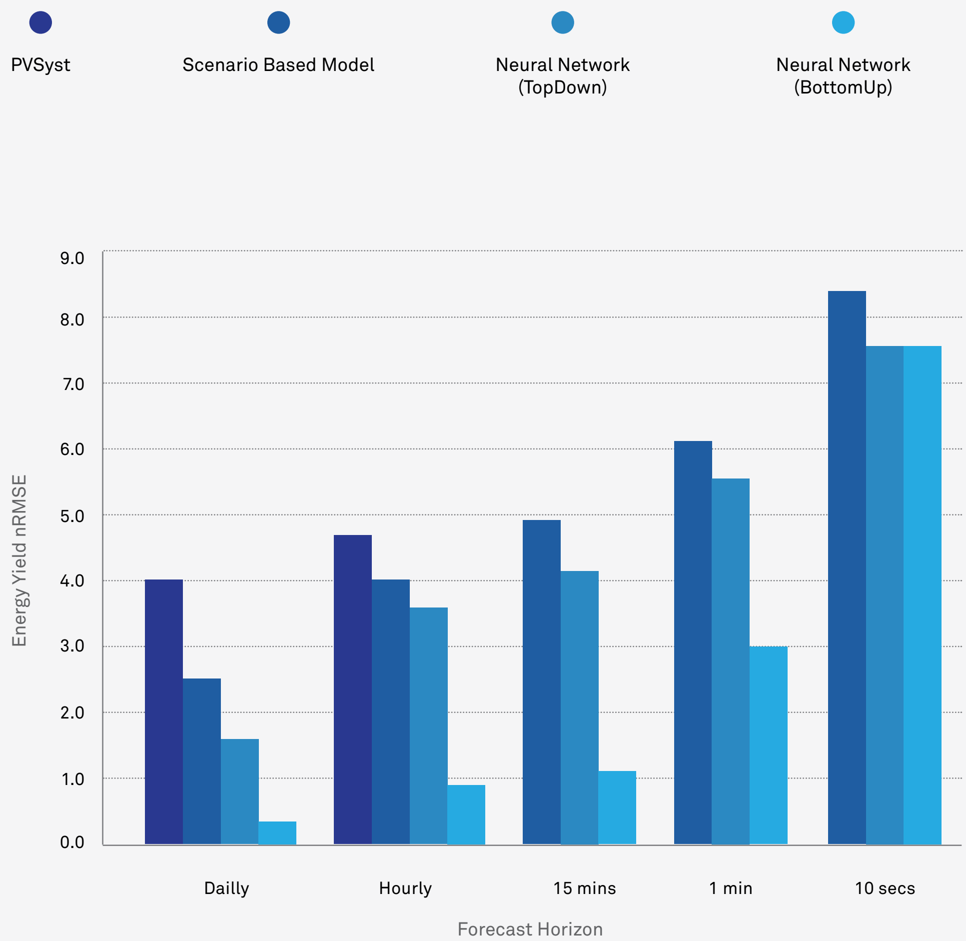


Figure 11: Normalized root mean squared error (nRMSE) of pv energy output forecasting models for different horizons

5.2. PV INVERTER CONTROL

The increasing deployment of PV systems connected to the grid can cause massive challenges for utility operators in terms of planning and operation. Through promising new intelligent methods like Smart Grids, the existing infrastructure can be used in a more efficient way, allowing a higher penetration of distributed and renewable resources. However, standardized and common communication systems are required to realize such intelligent methods. The IEC61850 inter-operability approach is one of the most promising solutions for multi-vendor information exchange in electric power systems today. However, many of today's PV inverters do not have an IEC61850 capable interface.

The *Performance Plus* consortium studied a cost effective way of upgrading the state-of-the-art PV inverters through a standard-compliant gateway device [36], [37]. The proposed solution uses the IEC61499 reference architecture for the implementation of the IEC81850 functions, thus making the inverter's functionalities accessible and ready for the future Smart Grid. Furthermore, the proposed solution allows the easier integration of methods for optimal energy management in, e.g., control of thermal and storage systems combined with PV generation. The first test results of the gateway controller were successful in both laboratory and operational test setups. However, after a few hours of operation the controller repeatedly stopped working in the operational test setup. Error logs point to high sampling frequency issues or software incompatibility as possible root causes. The proposed solution uses an open source implementation and further development and validation of it in a more complex real world demonstration scenario is encouraged by the consortium.

5.3. OPTIMAL CONTROL OF THERMAL SYSTEMS AND STORAGE

A system can be controlled optimally by looking at all plausible control alternatives and selecting the best one, where 'best' can be defined according to different objectives. A model for every component in the system is required in order to find the system response to the control inputs and thus allow selecting the optimal control inputs for the overall optimization of the system operation. Therefore, an accurate PV power output forecasting model is required to know how much energy can be expected to become available in the short term, as discussed in Sections 5.1.1 and 5.1.2.

5.3.1. MODEL PREDICTIVE CONTROL

Model predictive control (MPC) is the practical implementation of optimal control problems. The system is controlled using control inputs that are found by optimizing the model-predicted future behaviour of the system (Figure 12). The *Performance Plus* consortium has implemented this approach for the application of different use cases for optimal control of thermal systems and storage.

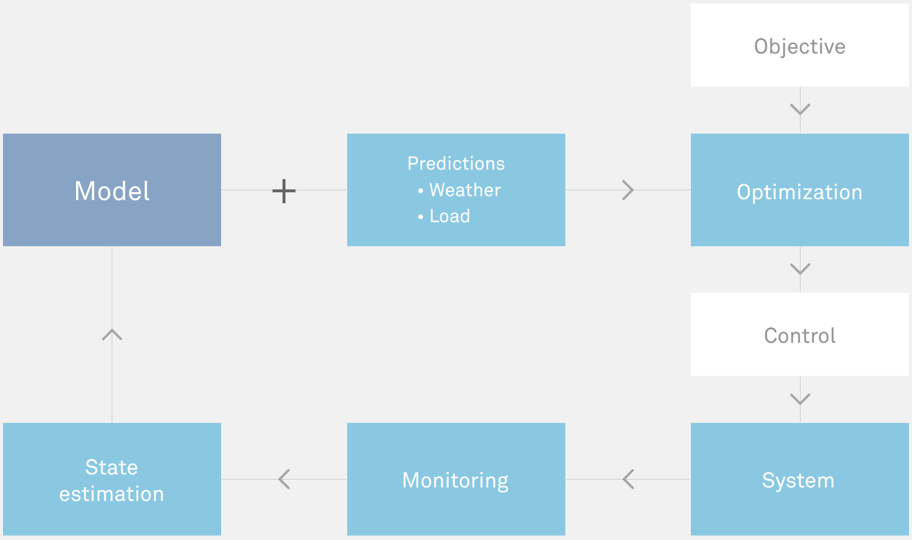


Figure 12 : Overview of the model predictive control framework

In the proposed MPC framework, a model of the system and predictions of the external and internal disturbances represent the future behaviour of the system. The control inputs that minimize the chosen objective are applied to the system. The changes in the system state are measured by a number of sensors and used for feedback. A state estimator ensures that the model keeps track of the current system state since not all state variables are measured. The model predictive controller runs through this loop repeatedly. The rate at which this loop is rerun depends on the dynamics of the system and the objective function. For the case studies analyzed within the *Performance Plus* project, this loop is typically repeated every 15 minutes.

Within the *Performance Plus* project, this approach has been implemented to thermal and battery systems which combine PV produced electricity with controllable loads. The main conclusions are summarized below. The detailed methodology and results of the overall demonstration and validation of these use cases are documented in the public report *Demonstration and Validation Report for Sensor and Monitoring System* [10].

5.3.2. APPLICATION TO THERMAL SYSTEMS

Thermal demand (heat/cold) of a large building can be integrated in the electrical energy management if the heat or cold is generated (at least partly) from electricity (heat pump or electrical resistance heating, compression refrigerator). The building thermal management is a flexible load which allows shifting the operating hours without jeopardizing thermal comfort. An MPC uses this flexibility by predicting the future system behaviour of the building and optimizing its heating/cooling control according to the given objective function.

Within the *Performance Plus* project, the MPC framework has been implemented on two different thermal use cases: a heating dominated case and a cooling dominated case. The electrical heating dominated case was applied to the 3E headquarters office building in Brussels. The building has a PV generation on the rooftop and a hybrid heat production system with two air-water heat pumps, a gas boiler and a tank for thermal energy storage. The objective was to heat the office building while minimizing the operating costs by optimally taking into account the PV production, the building thermal mass as passive storage and a small thermal storage tank as active storage. The results of the implementation of this use case are presented in [10]. The results show that the use of MPC during the winter in Belgium allows saving up to 30% of the heating energy costs compared to the initially used Rule Based Controller (RBC). Moreover, combined with PV, the MPC allows optimizing the system load profile because the heated building can be used as an extra thermal buffer, adding flexibility to the system. Different use cases comparing, for example, different tariff schemes or the use of an electrical battery system were analyzed by the consortium and the detailed results are presented in [10].

The cooling demonstration case analyzed within the project was performed in a cold store warehouse in Belgium. The objective in this case was to control the cooling system of the cold store warehouse to minimize the operating costs using the thermal mass of the building and the internal objects as passive storage. The results of the implementation of this use case are presented in [10] in detail. The results show that the use of MPC can improve the temperature management of a cold store warehouse by looking ahead and anticipating future cooling needs. Moreover, the cooling of a building can be further optimized with the integration of PV since the cooling needs of the building and the availability of solar irradiance are usually in phase. Furthermore, cold store warehouses are typically large buildings which allow the integration of roof mounted PV systems. The results show that MPC could, depending on the season, save up to 20% in netto operational costs compared to a Rule Based Controller, by optimally pre-cooling the building at night, while integrating the PV production generated power during the day. Different use cases comparing, for example, different tariff schemes or the use of an electrical battery system were analyzed by the consortium and the detailed results are presented in [10].

5.3.3. APPLICATION TO BATTERY SYSTEMS

The *Performance Plus* consortium analyzed the application of the MPC framework in PV plants coupled with battery systems for applications like on islands, where grids are often not very robust and the integration of PV plants is subject to restrictions. Such restrictions may include, among others, following a predetermined energy injection profile (e.g., trapezoidal profile). Therefore, the power production has to be forecasted and controlled. The objective in this case was to control the PV production to follow a predetermined daily injection profile and to optimize the size and use of a battery storage system. For the application of this use case, monitoring data from a 3 MW PV plant in Italy was used. The results of the implementation of this use case are presented in [10] in detail. The results show that the optimal battery size would vary from 45 kWh for winter days up to 1950 kWh for summer days. Although a larger battery would allow using all the PV generated power, the high price of a big battery storage system would compromise the overall gains. A smaller battery, on the other hand, reduces the battery storage system price, but leads to curtailing part of the generated PV power, reducing the profits from selling the energy. The application of the MPC allowed for selecting the optimal size of the battery. The battery size which generates the maximum mean daily gains for this use case was found to be 750 kWh. With the optimal battery size (750 kWh) the plant would generate 12% more daily gains than with the small battery (45 kWh) and 39% more than with the largest battery studied (1950 kWh).

The resulting power profile of the optimal mean battery size for four average days in different seasons is shown in Figure 13. The optimal mean battery size allows following the required trapezoidal profile while curtailing as little as possible the available energy. The smoothing in the trapezoidal profile in Figure 13, specially for winter months, is only caused by the averaging for the representation of this figure as in reality, every day follows a perfect trapezoidal profile.

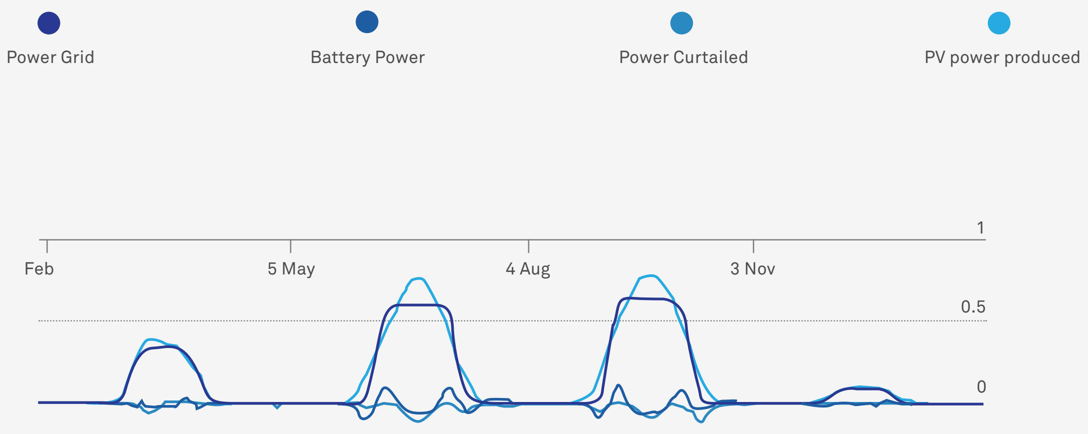


FIGURE 13: Normalized daily battery power profile per season [% of available solar irradiance] for an optimized battery size (750 kWh)

An overview of the curtailed energy for each battery size is presented in Figure 14. The results show that the small battery curtails almost 50% of the available yearly energy. During spring/autumn and summer months, the small battery has not enough capacity to store the daily maxima. Moreover, in winter the small battery cannot cope with the variability of the solar resource and therefore almost 60% of the available energy is curtailed. The optimal battery size on the other hand is optimized so the curtailment occurs only for high peak irradiance values when the power difference with the trapezoidal profile is too large. The largest battery would avoid this curtailment but at a very high price, thus compromising the overall gains.

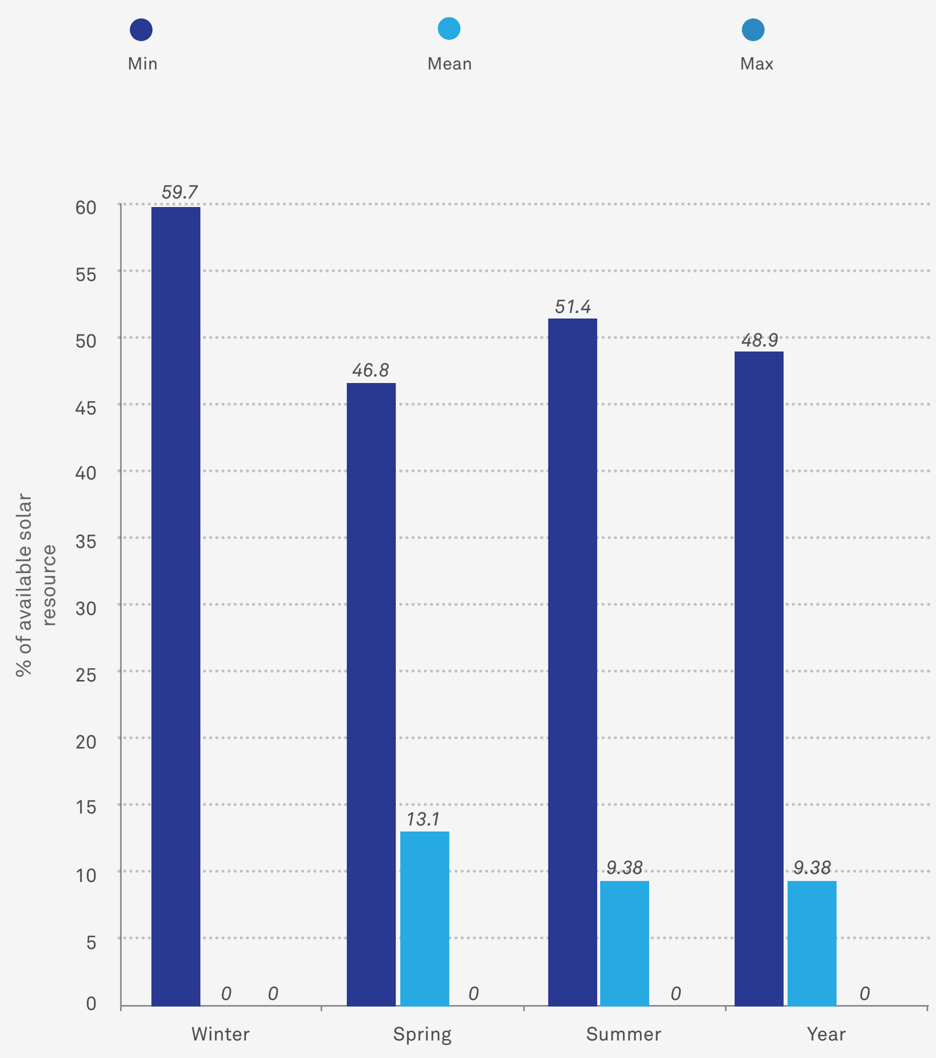


Figure 14: Energy curtailed [% of available solar energy] for a minimum battery size (45 kWh), optimal battery size (750 kWh) and a maximum battery size (1950 kWh)

Furthermore, the results show that the application of the MPC framework can improve the use cases of arbitrage, shifting electricity prices and PV production. In such scenario, the batteries are recharged with cheap power or penalized power if an injection profile is required. The stored energy is then used during periods of lower PV generation or higher market prices. Moreover, a battery can also be combined with a thermal system to form a hybrid application. This can have advantages for both applications combined and may reduce the size of the batteries, reducing the overall price of the system.

5.4. OVERALL SYSTEM PERFORMANCE

In the sections above, it has been shown that the accurate modelling of a system is essential for the application of optimal control methods. The specific model of the system determines the optimal control inputs and therefore, it should represent accurately the real observed performance in the field. However, advanced models as presented in Section 3.2.1 can have a relatively low execution speed, which makes them not ideal for this application. Therefore, a careful compromise between computing effort and accuracy must be found, which is implemented in the Grey-box Toolbox [38].
The results obtained during the validation and demonstration phase show that the overall system performance will depend highly on the application. Reducing the overall monetary cost is usually set as the main goal, as it is a quantitative and attractive measure. Moreover, when comparing system performance it is a good practice to quantify the objective functions in monetary terms. The overall system performance also depends on the boundary conditions as, e.g., the value of the feed-in tariff will influence the incentives for energy management.

Furthermore, the results show that the MPC allows integrating optimal design choices (e.g., battery sizing) with the optimal control of the system. It is therefore very well suited for efficiently realizing storage control and energy management with thermal systems and PV.

5.5. LESSONS LEARNED

In addition to the recommendations presented in the previous sections, the *Performance Plus* consortium has formulated the following observations with regard to energy management and control. Other stakeholders are encouraged to review them and build on the experience of *Performance Plus*.

- Sky images can be used to generate short-term forecast of irradiance. The first results obtained from the project show that sky image analysis provides very high resolution binary cloud masks but have limitations in deriving aerosol and cloud optical properties. However, the GHI retrieved from sky images using the proposed approach outperforms some of the state-of-the-art MSG satellite derived datasets. Furthermore, as no expensive radiometric measurement devices are required, the proposed approach reduces significantly the initial investment and operational costs. Nevertheless, an operational application may need several months for evaluation of real performance under different conditions. Moreover, the data processing is still relatively complex and not comprehensive. However, free and stable software is available for further development. Among the weaknesses identified by the consortium are the maintenance effort (regular cleaning of the camera is needed) and the data handling (amount and size of generated files).

- Forecasting the PV output power, especially under highly variable conditions due to the fluctuating nature of solar resource (short-term forecasting), requires accurate PV module models as, e.g., the model presented in Section 3.2.1. However, their relatively low execution speed is not appropriate for forecasting or nowcasting purposes. Nevertheless, a scenario based approach as the one introduced by the consortium in Section 5.1.2 can significantly speed up the execution time without compromising the accuracy and therefore, it can be used for short term PV output power forecasting as needed for precise on-line control.

- A cost effective way of upgrading the state-of-the-art PV inverters through a standard-compliant gateway device for multi-vendor PV inverters communication and control has been introduced and implemented within the project. The laboratory test showed trouble-free operation; however, reliability problems appeared after several hours of operation with a specific inverter in the field. Nevertheless, as the proposed solution uses an open source implementation, further development and validation of it in a more complex real world demonstration scenario is encouraged by the consortium.

- A heat pump with a coefficient of performance (COP) modelled as a constant value , which is often done in current practice, can overestimate the flexibility in the system and reduce the gains in a real implementation. Although using the heat pump is still advantageous over the gas boiler, the flexibility of the heat pump and the thermal buffer tank will not be used to their full extent when it is operated at a low COP. The rise in water temperature at the production side of the emission system not only lowers the COP but also increases the thermal losses and thus, the gains would decrease when trying to offer flexibility. The implemented optimal control solution avoids unnecessarily increasing the emission system temperature for storing heat.

- A heating case is out of phase with the PV production (seasonal and diurnal). In the use case implemented by the consortium, the MPC could only run in the cold and mid-season. The use of a reversible heat pump which can offer cooling in mid- and hot season would allow for a better match of PV with the controllable load.

- Continuous and proactive care of the monitoring system from the heating use case implemented by the consortium in the 3E Kalkkaai office building was required. The data handling from all sensors and components installed across the building and the maintenance of the communication system is cumbersome. The implementation of a robust system is very important but time intensive. Therefore, limiting the amount of sources for inputs to the optimal control framework is crucial.

5.6. TAKEAWAYS

The use of inexpensive sky imagers for the observation of the atmospheric state is a valuable addition to meteorological measurements and allows shortest-term irradiance forecasts;
Accurate irradiance forecasts require a combination of different data sources and forecasting models to consider the large variability of solar irradiance;
The use of MPC during the winter in Belgium allows saving up to 30% of the heating energy costs compared to the initially used Rule Based Controller (RBC);
Combined with PV, the MPC allows for harnessing flexibility from any controllable load;
The use of MPC can improve the energy management of a cold store warehouse by optimally pre-cooling the building with PV generated power;
The MPC allows integrating optimal design choices (e.g., battery sizing) with the optimal control of the system. It is therefore very well suited for efficiently realizing storage control and energy management with thermal systems and PV.

6

Conclusions

6. CONCLUSIONS

The *Performance Plus* project has developed models, methods and tools to optimize and enhance the performance, reliability and lifetime of commercial PV systems. All results were validated and demonstrated with empirical data from a total of 25 PV systems across Europe. Novel methods have been introduced and validated for advanced PV module modelling, short-term forecasting, testing and diagnostics, advanced PV system monitoring techniques, and integrated energy management and storage control. Some of these project results are already being transformed into proven marketable products. The results of the validation and demonstration phase are publicly available in the technical reports [10] and [11]. Additional reports and scientific publications are available on the project website:

www.perfplus.eu

The conclusions below are divided in three subsections according to the structure of this report.

PV Plant Design

The assessment of the solar resource was identified as the most important source of uncertainty in long-term yield estimates for PV. Independent of whether the solar resource is measured with a pyranometer, a silicon sensor or if it is derived from satellite estimates, the *Performance Plus* consortium recommends to always perform a quality control of the data and to properly assess and report the related uncertainties. If appropriate, ground measurements and satellite estimates should be combined as described in [1] in order to reduce the uncertainty of the solar resource assessment. This will help developers and investors to evaluate more carefully the financial risks during the design phase of the PV plant.

For PV array modelling in situations where a high accuracy of the output power of a PV array is required in space and time, the use of fine-grain thermo-electric models as described in [2]–[5], integrated with a transient inverter model is recommended. As the PV inverter plays a key role in the power conversion chain of the PV system, the consortium recommends performing additional tests as described in [6]. Additional accelerated stress reliability tests as described in [8] can help to qualify PV inverters for real world applications under different climate conditions. By using a tool that combines advanced PV component models as described in [9], cost-efficient integration of the different PV system components can be reached through a holistic cost optimization approach.

The current IEC standard qualification and test procedures do not determine the tendency of performance degradation during the PV modules lifetime. Within the *Performance Plus* project, new indoor test procedures for degradation mechanisms were proposed. The new indoor test procedures will allow for determining the tendency of performance degradation mechanisms caused by potential induced degradation (PID) and dynamic load stress during the PV module's lifetime [7]. These new procedures continue under development within the IEC working groups.

PV Plant Operation

An innovative sensor that measures global, diffuse and direct irradiance has been developed within the project. The developed irradiance sensor, called ESA, significantly improves both, the costs and the ease of operability in the measurements of solar irradiance. The reduced monitoring costs and maintenance efforts allow not only for small PV plants to perform solar irradiance monitoring, but also for medium to large PV plants to perform distributed rather than single-point monitoring. Furthermore, in the field of energy management and optimal control of thermal systems, it enables the active optimization and fine-tuning of heating and/or cooling related energy use.

The *Performance Plus* consortium has developed a methodology able to automatically characterize the physical parameters of a PV array, and to provide insight in the root causes of performance losses. This methodology has been called the PV *Health Scan* and is documented in [30]. The methodology allows for the systematic analysis of operational data in an efficient way, identifying how design choices and O&M practices lead to inferior or on the contrary, superior performance in the field. The results show that, thanks to the application of the PV *Health Scan* methodology, the performance could be increased significantly (by 10% and more) for some PV plants.

A set of procedures and tools for PV system field testing, designed to detect issues in PV plants affected by under-performances, have been developed within the project. The developed methods include tools to improve laboratory testing and tools for outdoor testing of PV plants, including both PV modules and PV inverters. The tools for laboratory testing focus on an improved PV module sampling procedure with a clear definition of number of PV modules to test, selection of modules and a final lot acceptance report. Furthermore, the procedures and tools for PV system field testing aim at detecting different modes of degradation (PID, optical, electrical or mechanical damage) using traditional light *I-V* curve measurement and innovative dark *I-V* measurement techniques. Beyond these measurements, the consortium implemented numerical methods to extract parameters in order to differentiate between failures and degradation modes that can happen in operational PV plants.

Energy Management and Control

The *Performance Plus* consortium investigated the combination of different forecast models to further reduce the forecast error of the solar resource. Furthermore, the consortium has focused on irradiance forecasting using sky imagery [32]. Images from ground-based sky cameras enable a detailed analysis of the cloud distribution and their motion vectors. The overall results of the validation show that sky image analysis provides very high resolution binary cloud masks, but has limitations in deriving aerosol and cloud optical properties. However, as no expensive radiometric measurement devices are required, the proposed approach reduces significantly the initial investment and operational costs. Moreover, the results of the first validation show that the GHI retrieved on the basis of sky images and a machine learning approach outperforms MSG satellite derived data (HELIOSAT-method [34]) for the measurement site of the University of Oldenburg.
The thermo-electric model ([2]–[5]) developed within the project is suitable for simulating non-steady-state and non-uniform illumination conditions. However, the relatively low execution speed of this model would not allow it being used for on-line forecasting or nowcasting purposes. Therefore, the *Performance Plus* consortium has developed a technique that significantly speeds up the computation without compromising

the accuracy. The developed model uses a combination of a one-time a priori scenario clustering phase and a continuously executed scenario detection phase during operation. The results show that this approach is more suitable than the state-of-the-art methods, especially under highly variable weather conditions and for short forecasting windows where the neural networks would have to be re-trained for a long time period to obtain the most accurate results.

A cost effective way of upgrading state-of-the-art PV inverters through a standard-compliant gateway device has been introduced and implemented by the consortium. The first test results of the gateway controller were successful in both laboratory and operational test setups. However, reliability problems appeared after several hours of operation in the operational test setup. Nevertheless, since the proposed solution uses an open source implementation, further development and validation of it in a more complex real world demonstration scenario is encouraged by the consortium.

The *Performance Plus* consortium has selected MPC as an optimal control approach for the overall optimization of the system. This approach has been implemented on different use cases for optimal control of thermal and energy storage systems that combine PV produced electricity with controllable loads. For accurate yet fast modelling of the thermal systems for optimization, the so-called Grey-box Toolbox [38] has been developed. The MPC along with an adapted grey box model was successfully demonstrated on the 3E headquarters office building in Brussels. The results show that the use of MPC during the winter in Belgium allows saving up to 30% of the heating energy costs compared to the initially used rule based controller. Combined with PV, the MPC allows harnessing flexibility from any controllable load. The results show that the use of MPC can improve the energy management of a cold store warehouse by optimally pre-cooling the building with PV generated power. Furthermore, the results of the implementation of different use cases show that the MPC allows integrating optimal design choices (e.g., battery sizing) with the optimal control of the system. It is therefore very well-suited for efficiently realizing storage control and energy management with thermal systems and PV.

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