INTRODUCING 'PEARL PV': PERFORMANCE AND RELIABILITY OF PHOTOVOLTAIC SYSTEMS - EVALUATIONS OF LARGE-SCALE MONITORING DATA

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ABSTRACT: This paper will introduce a recently initiated COST Action titled PEARL PV and show its 4-year research and work plan with the aim to create exposure, receive feedback from various stakeholders and involve new participants to this research network. The aim is i) to improve the energy performance and reliability of photovoltaic (PV) solar energy systems in Europe leading to lower costs of electricity produced by PV systems by a higher energy yield, ii) a longer life time eventually beyond the guaranteed 20 years as specified by manufacturers, and iii) a reduction in the perceived risk in investments in PV projects. This objective will be achieved by analyzing big data of the actual monitored long-term performance, defects and failures in PV systems installed all over Europe to quantitatively determine the absolute influences of components rated performance, key design of systems, installation, operation, maintenance practice, geographic location and weather factors on the performance, performance degradation over time and failure modes of these PV systems. The PEARL PV project aims at the formation of an inclusive network of PV system researchers, data resources that will be analyzed by researchers and experts that can include more-nuanced evidence-based reliability in PV system evaluation methods and simulation and design tools. The COST Action PEARL PV assembles an inclusive partnership network of PV system researchers with experience with PV monitoring and simulation, with solar resources, and with PV operators who collectively bring together their ongoing work to contribute to the collation, analysis and interpretation of an agglomeration of PV system performance data in Europe.
Keywords: PV systems, Monitoring, Energy performance, Durability, Simulation, Building Integrated PV

1 INTRODUCTION

PEARL PV is the abbreviation for 'Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data' and was initiated in October 2017 for the following reasons. PV systems can achieve a long-term pivotal position in the future single European energy market, only by ensuring effective performance, high reliability and prolonged durability [1, 2]. PV solar systems have now become an established part of the electrical energy mix in standalone and grid-connected applications. Their modularity, consisting of PV modules, inverters, other power electronics and support structures, make them applicable at the fullest range of scales from hundred watts to hundreds of megawatts. At present PV systems are the most dominant solar technology in the world with an installed capacity exceeding 400 GW (at the end of 2017) which significantly more than installed solar thermal systems and concentrating PV. This is mainly due to significant costs reductions in the past decades, while the market for PV systems has grown at 44% per annum. Recently Power Purchasing Agreements for PV systems were reported below 2 cents per kWh in Saudi Arabia. In 2016 in Germany and Italy resp. 6 to 8% of the annual electricity was generated by PV systems, while across Europe in 2017 PV systems account for 4% of the electricity demand. Targets for further PV deployment have been set, e.g. the International Energy Agency expects 3 TW of PV systems to be globally installed by 2050 representing about 11% of the global electricity production. With such large numbers, reliability and performance are of paramount importance with a timeline for the next 20 years looking at the horizon of energy scenarios in 2050. As the majority of all PV systems have been installed in the past 10 years, each single installation can provide only a limited insight into the long-term performance and reliability of PV systems. The challenge is therefore to learn from the experience and information as embodied in the monitored performance of many PV systems. Important interlinked non-technical factors driving growth in photovoltaics deployment include:

- Government regulations and mandates and obligations for renewable power,
- Falling prices for all PV system components,
- Take-up of third-party funded PV array ownership models,
- Availability of dedicated feed-in tariffs or other financial (tax) incentives for PV systems,
- Need to decrease the global warming environmental impact of electricity generation,
- Reducing dependence on centralized generation electric utilities,
- Scalable, silent and clean operation enables PV systems to be used readily in smart cities and in building integrated PV systems.

Figure 1: 30 countries that take part in this COST Action PEARL PV by 21 September 2018, indicated in orange.

Well-executed PV system research requires long term collaboration in geographically distributed research networks due to the strong relation between PV performance, geographically distributed climates and related solar resource assessments. Also this will be required due to the global spread of data on energy performance of PV systems and failure statistics of their components. Therefore the COST Action PEARL PV assembles an inclusive partnership network of PV system researchers with experience with PV monitoring and simulation, with solar resources, and with PV operators who collectively bring together their ongoing work to contribute to the collation, analysis and interpretation of an agglomeration of PV system performance data in Europe.

The network includes (i) experts that can make the most-nuanced evidence-based consideration of reliability in PV systems (ii) experts that have the ability to integrate this knowledge in evaluation methods, simulation models and design tools and (iii) the direct participation of end users to ensure there will be knowledge about their insights and perspectives. The project will therefore contribute to the development of a mature research field for PV system analysis in relation to irradiance potentials, long term PV performance, and PV grid interactions in an international context inside and outside Europe, see Figure 1. At present in total 31 countries, namely 30 at the European continent and the USA are a member of the PEARL PV network. The network is aiming at involving all 36 European COST member countries and if possible many more countries in the further world.

2 MAIN OBJECTIVES

PEARL PV aims to increase performance and lower costs of electricity produced by photovoltaic (PV) solar electricity systems in Europe via (i) obtaining higher energy yields, (ii) achieving longer operational life time (beyond the 20 years usually guaranteed by manufacturers) and (iii) lowering the perceived investment risk in PV projects. These objectives will be achieved by a cooperative European COST Action partnership, collating and analyzing a very large aggregated set of monitored long-term PV System operational performance data, with a focus on understanding defect and failure of PV systems installed across Europe, in the context of integration of PVs facilities into grids, and the impact of regional climate characteristics on the generation of PV energy. This data will be used to determine quantitatively:

- the absolute influences of (i) components' rated performance, (ii) system design, (iii) installation type, (iv) operation and maintenance practice, (v) interactions with grids, (vi) geographic location and (vii) weather and climate conditions;
- on (i) performance degradation over time and (ii) failure modes as they affect (i) economic viability, (ii) securing project investment, (iii) environmental sustainability (iv) security and predictability of electricity supply and (v) diversity and distribution of electricity supply;
- to (i) improve the electrical design of PV systems, (ii) achieve optimal sizing via the use of simulation models, (iii) enhance expected system efficiency, (iv) ease maintenance, (v) achieve high reliability and (vi) demonstrate excellent durability.

For this purpose 5 Working Groups have been set up that will conduct research using a shared data bank and shared simulation tools and models to analyze and compare these data that are collected in this data bank, see Figure 2. The 5 Working Groups are focused on (WG1) PV monitoring, (WG2) Reliability and durability of PV, (WG3) PV simulation, (WG4) PV in the built environment and (WG5) PV in grids. In the following sections (2.1 to 2.5) the objectives and activities in each Working Group will be introduced.

2.1 WG1: PV monitoring

The main objectives of WG1 are to:

1) identify relevant data to be collected to properly assess PV performance of installed PV systems in the field and on rooftops,
2) design guidelines for the collection,
3) set-up a database, and
4) guidelines for database access.

These objectives will be achieved by analyzing data of the actual monitored long-term performance, defects and failures in PV systems installed all over Europe to quantitatively determine the absolute influences of components rated performance, key design of systems, installation, operation, maintenance practice, geographic location and weather factors on the performance. This also will allow to study performance degradation over time and failure modes of these PV systems. A first version of the open database is planned for fourth quarter of 2018. At present WG1 consists of 30 members.

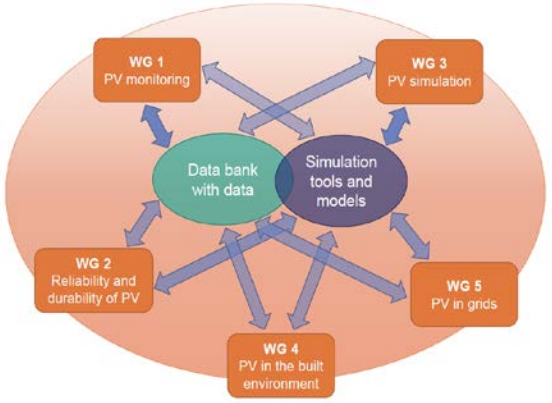

Figure 2: The 5 Working Groups of COST Action PEARL PV in relation to a shared data bank and simulation tools.

2.2 WG2: Reliability and durability of PV

The main objectives of WG2 are to find a proper definition of reliability and durability metrics for PV modules, components and systems as well as to identify relevant data to be collected to measure reliability and durability. WG 2, which currently consists of 30 members, will address the following problems and research questions:

1) Definition of reliability and end-of-life considering different views of PV stakeholders and different technologies.
2) How to test reliability?
3) Can reliability, lifetime or end-of-life be modelled from short term testing?
4) Can available models for single effects or single materials be combined to an comprehensive PV module lifetime assessment method?

The planned outcome is an extensive review paper to be published in 2020. Contributions are still welcome.

2.3 WG3: PV simulation

WG3 considers the use of modelling tools that are used to simulate the performance of PV devices and systems, both for prediction and assessment of performance. The main objectives are to

1) identify and classify the current PV simulation models by scope and usage category, (
2) provide access to information on PV solar electricity simulation models,
3) compare the performance of various models and
4) share the knowledge originating from this study with the PV community.

The initial activity of WG3 has been to issue a software usage questionnaire to establish the tools commonly used by the community and to obtain information on the way in which those modelling tools are utilized. Initial analysis has been based on the response of 33 members of the PEARL PV community, who identified 14 different packages that are regularly used, ranging from solar irradiance models to system simulation packages. The survey is being used to inform the scope of the model comparisons to be performed over the next few months. Further responses to the survey are welcome. The survey can be accessed on the PEARL PV website.

2.4 WG4: PV in the built environment

The use of PV in the built environment is the focus of the WG4, with the main aim of improving the performance of PV systems in such environment, and improving the ability to predict the behavior of PV in operating conditions. The starting point is the systematization of existing knowledge the COST PEARL participants share from previous or on-going projects, publications, and thematic networks they are involved in.

The composition of the participants is strongly multidisciplinary, with focus on: architecture; building technologies and PV integration; technology and PV systems; standardization, norms and regulations; data monitoring, modeling and simulations; reliability, testing, components, materials.

Within the WG4 there are two main tasks:

1) Collection of information in the data server of this Action about PV in the built environment, from realized projects, publications and information retrieved from internet, together with PV experts, architects, installers, construction and building services engineers and city/urban planners.
2) Identification of required data and appropriate simulation models to be used in the framework of PV systems in the built environment given the challenges of (i) shading by neighboring buildings, (ii) building and planning codes and regulations and (iii) energy performance norms that apply to and/or are required for, buildings.

About 20 experts are participating in the activities of the WG4.

Up to now, a review of trends in development of simulation models and tools has been prepared, with particular emphasis on integration in the building information modelling (BIM) environments and on application in early design stages. Considering available reviews [53], recommendations [54] and recent explorations in domain of simulation tools, [55], [56], [57], as well as a preliminary examination performed in first grant period of the PEARL PV Project-WG4 including 18 tools, a set of trends has been identified, clearly indicating a converging development of PV simulation tools and BIM platforms.

2.5 WG5: PV in grids.

WG5, currently composed of 27 participants, aims at contributing towards PV systems that are better integrated into the grid, that perform better, and whose operation under real-world conditions is better understood. This WG will use information from WG1, WG2 WG3 and WG4 on PV monitoring, reliability and durability and PV simulation respectively and information from communications with PV experts, electrical engineers, utilities, smart grid experts and meteorologists. These objectives will be achieved by exploring five different complementary pathways:

1) PV power forecasting
2) PV power fluctuations for grid operators
3) PV power quality in the grid
4) PV energy storage and management strategies
5) PV performance and fault detection

2.6 Training Schools

Adding to the research activities in the Working Groups, COST Action PEARL PV also aims at knowledge dissimination to young researchers by means of Training Schools. The topics that will be addressed by these annual Training Schools are connected and overlapping with the content of the Working Groups. Topics that have been identified for the period of 2018 to 2021 are as following:

1) 2018: Monitoring and simulation of the performance and reliability of PV systems in the built environment.
2) 2019: Evaluation of the performance degradation of PV-systems – influence factors, failure modes and their detectability and affect on economic viability.
3) 2020: Simulation tools and models for the forecast of system efficiencies of PV plants – with focus on environmental and integration aspects.
4) 2021: Potential of monitoring tools and advanced operation and maintenance practice for security and predictability of PV performance.

3 DISCUSSION AND RELEVANCE

Whilst the highest efficiencies for small PV cells in laboratory contexts are near 32%, commercial PV modules have a maximum rated efficiency of close to 22%. In operational PV installations these efficiencies decline further to be in the range of 13 to 17%, because a PV system [3-5] (i) is exposed to solar irradiation intensity, collimation and spectra that vary but are different from those under which standard rating procedures are conducted, (ii) is subject to soiling, (iii) has a lower than expected inverter efficiency, (iv) may have inefficient maximum power point tracking and (v) suffers thermal de-rating of PV modules (e.g. 0.4% loss per °C for silicon PV modules). System efficiency strongly depends on (i) local meteorological conditions, (ii) PV module technology (mono- or multi-crystalline silicon, thin film or organic PV), (iii) other electronic components involved (inverters, batteries etc.), (iv) the system configuration (e.g. local shading) and (v) the operation and maintenance of the system. Key factors determining the optimal performance of a PV system are shown in Figure 3.

There are extensive international IEC and SEMI [6,7] conformity standards to which PV modules and systems must comply to assure users and investors of the long-term value of their systems. However, as relatively few studies have considered the actual realised longterm performance of PV systems in use [8-32], there is a lack of collated comparable data from many installations on actual system and component reliability and durability [33-36]. It is imperative to find relationships between system performance over time and reliability in the long run.

Optimal design of switching converters for the integration and optimal exploitation of photovoltaic solar electricity systems into the electric grid remains a crucial issue often debated in the recent power electronics literature [37-39]. The installed capacity of operational PV systems has increased at a much faster rate than the development of adequate grid codes to effectively and efficiently manage high penetrations of PV into the distribution system.

Figure 3: Key factors that determine the optimal performance of PV systems.

Management strategies vary considerably by country, some still have an approach that PV systems should behave as passive as possible, whereas other countries demand an active participation in grid control. For smart grid scenarios with a high penetration of distributed renewable energy generation into the electric grid, PV systems have to supply ancillary services to the distribution grid, in particular voltage and frequency regulation that maintain grid stability [40-43].

Therefore this COST Action compares monitoring data with results from simulation models for multiple photovoltaic installations, to define the range of applicability of each simulation model and make recommendations for improvement of simulation models to include reliability and durability. This COST Action creates a network that will uniquely bring together groups in Europe who have long-term PV system performance measurements with groups that have developed and can further enhance simulation models for PV reliability/durability. The aim is to understand the key factors influencing real-life relations between performance, reliability and durability [44] to ensure that this insight is embodied in (i) design methodologies [3] (ii) conformance standards [6], (iii) monitoring methods, (iv) predictive models for reliability/durability [16], and (v) system performance indicators such as efficiency, final yield and performance ratio [8,23,45,46]. This includes, for examples, replacement of components, and correcting irradiance or temperature mismatches in maximum power point tracking [47] and effects of application of PV systems in buildings [48-52]. It will produce a consolidated input/output performance chart that places all annual systems performance in a common format, to determine trends in system performance with (i) type of installation, (ii) components types (PV, inverters etc.) (iii) location,(iv) date of installation. This will be used to produce evidence-based design recommendations [58] based on (i) a systematic categorization of typical failures, (ii) their statistical distributions and (iii) both estimated and measured their impact on PV performance.

Indicators, which will be used to quantify and compare the performance of PV modules and PV systems, are among others: performance ratio (PR), final yield (Yf) and temperature-corrected efficiencies ($\eta 25^oC$). These indicators will be related to available irradiation (H) and modes of operation and eventual failures. For reliability and durability research, firstly performance data – as indicated above – will be used to determine the rate of degradation of PV module and systems, secondly failure modes will be collected, identified and statistically evaluated. This evaluation will happen in the context of among others, location, hence irradiation, life time of the PV modules and PV systems, typical components and modes of installation, system operation and integration with the grid as well as maintenance schemes.

4 SUMMARY AND CONCLUSION

This paper presents a recently initiated COST Action entitled PEARL PV and shows its 4-year research and work plan with the aim to create exposure, receive feedback from various stakeholders and involve new participants to this research network.

In the forthcoming period PEARL PV will continue organizing events such as Seminars, Workshops and Training Schools to reach out to a large audience of PV experts, young researchers and companies. Before the end of 2018 the data bank containing PV monitoring data should become available as well as a complete workplan for the further implementation of research and dissemination activities in the period of 2018 to 2021.

For more information about this project, registration for participation in this network and for future events of PEARL PV please visit the website of this COST Action at https://www.pearlpv-cost.eu/ and the project page of this Action at the COST Association at http://www.cost.eu/COST_Actions/ca/CA16235.

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