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Performance and degradation in silicon PV systems under outdoor conditions in relation to reliability aspects of silicon PV modules – Summary of results of COST Action PEARL PV

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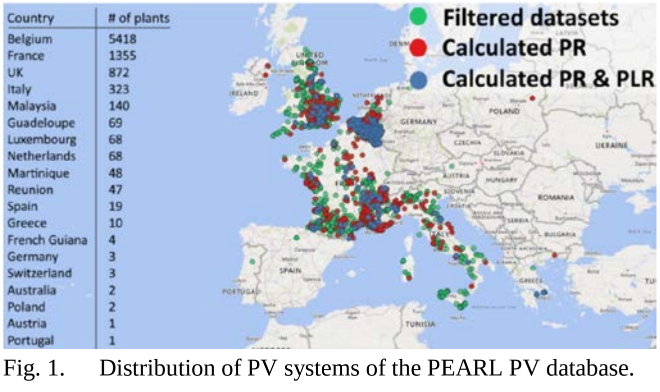
***Abstract* — This paper presents the main results of COST Action PEARL PV, aiming at finding connections between the observed performance of monitored PV systems and degradation causes and failure modes according to literature with a focus on the most dominant technology among installed PV modules, namely silicon PV. It is found that there there exists a great potential for performance improvements, though in practice it is difficult to identify exact causes for failure and underperformance.**

I. INTRODUCTION

Understanding of degradation and failure of silicon photovoltaic (PV) modules that have been installed in the field, is one of the key factors to enhance the lifetime of PV systems and, hence, reduce the cost of PV electricity produced. Hereby the basic assumption is that better insights about energy performance, degradation and failure modes can lead to mitigation of causes of less than expected operational lifetime of PV systems. Hence, improving the energy performance and reliability of PV systems has been the focal point of research in COST Action PEARL PV [1] (2017-2022). This project, funded by the COST programme of the European Commission, has been executed by hundreds of PV system experts from 40 countries, which has resulted in a database with monitoring data of thousands of PV systems, see Figure 1, as well as numerous publications among which 40 in journals [2].

COST Action PEARL PV is one of the few academic networks in the rapidly growing field of PV system research. This research is essential because in the past decade the number of installed PV systems has been steadily growing at 20 to 40% per year, resulting in 1 terawattpeak (TWp) of cumulative installed power worldwide in 2022, contributing about 5% to the global electricity demand.

The PEARL PV network is strongly focused on assessing the actual performance and durability of already installed PV



Country	# of plants
Belgium	5418
France	1355
UK	872
Italy	323
Malaysia	140
Guadeloupe	69
Luxembourg	68
Netherlands	68
Martinique	48
Reunion	47
Spain	19
Greece	10
French Guiana	4
Germany	3
Switzerland	3
Australia	2
Poland	2
Austria	1
Portugal	1

Fig. 1. Distribution of PV systems of the PEARL PV database.

systems in the short and long run. This task is usually not taken care of by installers, utilities and/or DSOs. This paper will summarize some of the most important results of this COST Action, aiming at finding connections between the observed performance of monitored PV systems and degradation mechanisms and failure modes according to literature. This study will focus on the most prevailing technology among installed PV modules, namely silicon PV. Next, in Section II the research set-up will be described, followed by a summary of results in Section III, and a discussion, conclusions and recommendations for future research in Section IV.

II. RESEARCH SET-UP

The research has a two-fold approach; namely, on the one hand, quantification of the energy performance of a large fleet of PV systems by analytical monitoring and analysis [3], and on the other hand, identification of possible degradation mechanisms and failure modes on the basis of extensive literature studies [4, 5]. These two approaches are connected and discussed, leading to a set of recommendations.

A. Performance analysis of monitored PV systems

To capture degradation in the field, an performance analysis has been executed of monitoring data of over 8400 PV systems [3], see Figure 1. Data have been analyzed regarding the actual monitored long-term performance to quantitatively determine the absolute influences of geographic location, irradiation and ambient temperatures, key system design features such as system components' rated performance and installation types, failure modes, operation and maintenance practices, and performance degradation over service time of these PV systems. The monitoring data have been stored in the PEARL PV database as time series with 10-minutes resolution ranging from one to four years from 2010 to 2016. These time series are covering the following metadata: installed capacity, latitude, longitude, azimuth, and tilt angle of the PV modules. ERA5 reanalysis data are used as irradiance data.

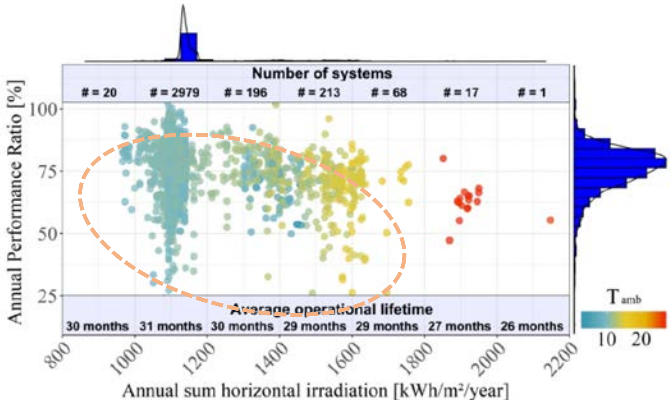


Fig. 2. Annual sum of horizontal irradiation [kWh/m 2/year] versus annual PR [%] categorized by average ambient temperature [∘C] for PV systems in the PEARL PV database as shown in Figure 1.

B. Degradation and failure phenomena

To reduce degradation rates, it is imperative to have insights into degradation and failure phenomena. Hence, an overview is given of the state-of-the-art knowledge on the reliability of silicon PV modules [4, 5] on the basis of a review of about 250 publications. This overview consists of two parts: first, a brief contextual summary about reliability metrics and how reliability is measured, and . second, a summary of the main stress factors and how they influence module degradation.

III. RESULTS

A. Performance analysis of monitored PV systems

The PV plants analyzed are small residential systems with silicon PV modules with a median installed capacity of 6 kWp, primarily installed in Europe, with an average field age of 30.5 months. From the analysis, it is found that the annual mean performance ratio (PR) across all systems was 76.7 %; with an average yield of 954.9 kWh/kWp per year [1] as seen in Fig 2. It can be concluded that the PR is far below the expected range of 80 to 90 % due to outage, failure, shading, and climate conditions, in particular high irradiation (>1400 kWh/m^2/year) and ambient temperatures (> 14 $^{\circ}$C). Performance loss rates (PLR) were also determined on the basis of an analysis of monitoring data. Average performance losses between 0.74 %/year and 0.86 %/year were calculated depending on the method used

B. Degradation and failure phenomena

An extensive literature review [4,5] has resulted in a summary of the main stress factors defined as the causes of PV modules degradation. Given the findings shown in Section III.A, it is very important to understand how stress factors influence PV module degradation. The review of degradation and failure modes has been focused on the level of individual PV modules' components.

In general, stress factors can be categorized into external and internal stress factors, where external stress factors are related to environmental conditions, such as irradiance, temperature, moisture, mechanical load, soiling and chemicals, while internal stress factors are caused by the PV module architecture and the bill of materials (BOM) of PV modules (including BOM incompatibility) and processing related

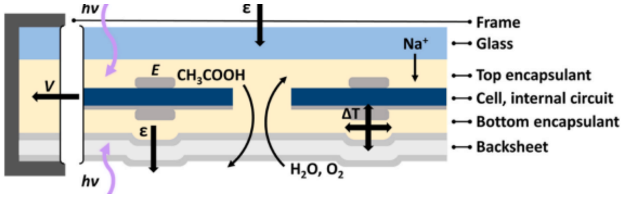


Fig. 3. Some common PV module stressors for a silicon wafer-based PV module, including light (hv), strain (ε), voltage bias (V), chemical diffusion, ingress and egress (CH3COOH, H2O, O2, Na+), electric field (E), and thermomechanical strain (ΔT).

effects. Usually, these stress factors occur simultaneously as seen in Fig. 3. Next, from the existing literature, degradation and failure modes could be identified that generally occur in PV technologies, as shown in Table 1, enabling to draw relationships between stressor, PV module components, failures and effects as shown in Figure 4.

TABLE I
Common Degradation and Failure Modes of PV Module Components and Their Potential Effects.

Component	Degradation	Failure Modes	Effects
Frame	Corrosion	Warpage	Increased risk of module damage
Glass	Glass corrosion	Breakage, soiling, abrasion	Reduced current, hotspot formation
Encapsu-lant	Photo-oxidation	Discoloration delamination	Reduced current, increased corrosion
Internal circuit & TCO	Corrosion	Fatigue, cracks	Reduced current, cell isolation, hotspot formation
Solar cells	PID, LID, LETID	Cracks, cell isolation (cracks)	Reduced power, hotspot formation
Back-sheet	Photo-oxidation, hydrolysis	Discoloration, dela-mination, cracks	Increased corrosion, isolation failure
Junction box	---	Arcs delamination	Electrical fault, detachment

IV, Discussion, Conclusions and Recommendations

Finally, on the basis of Fig. 4, we dare to draw the conclusion that a mixture of external and internal stress factors makes it difficult to uniquely identify the causes for failure and the effects at the level of PV module output as well as to represent each failure in relation to effects and vice versa. Evenly important, also inverters, electronics and other BOS can show failures, and hence affect the system performance. In practice, for small residential PV systems, average performance losses between 0,74%/year and 0,86%/year have been measured; however, most PV systems don’t achieve the expected performance ratio (PR) of 80 to 90%, instead an average PR of 77% is achieved here. Hence, there exists a great potential for performance improvements. Though it is difficult to identify exact causes for failure and underperformance, the present terawatt PV market demands for better insights into long term performance and degradation mechanisms of silicon PV systems. This can be realized by better interaction and data sharing between upstream and downstream. Therefore, it is also advised that more research efforts should be directed towards statistically quantifying and mitigating degradation mechanisms and failure modes of PV systems.

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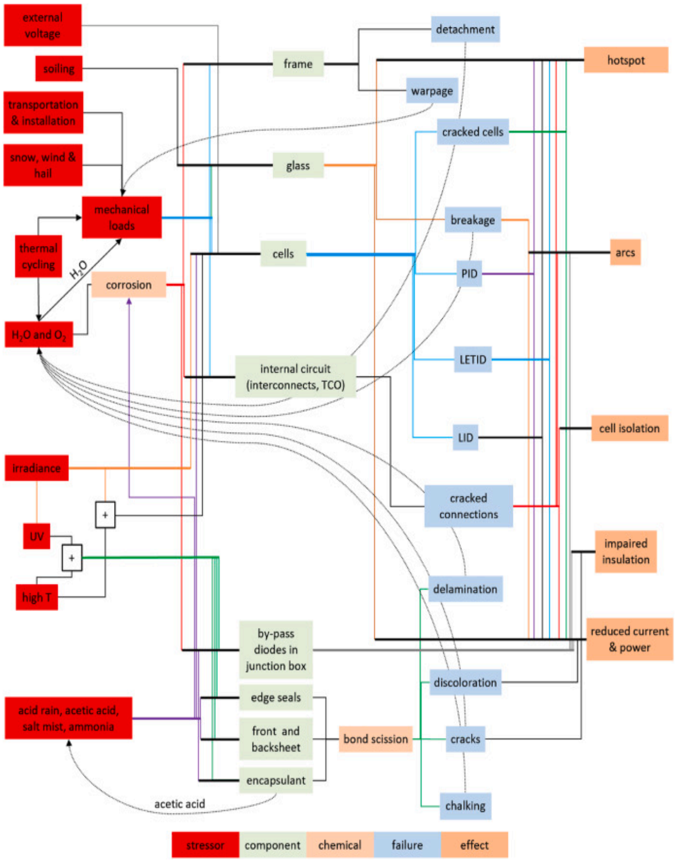

Fig. 4. Flow diagram representing the relationships between stressor, component, failure and effect.

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