



## RESEARCH CHALLENGES IN PV RELIABILITY

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## RESEARCH CHALLENGES IN PV RELIABILITY

Reliable solar PV power plants will deliver the expected performance throughout their entire service life. They will experience very limited component degradation, failures or system down-time. Improving reliability means derisking electricity production and return on investment of PV systems. Mitigation of risks supports the bankability of PV systems and serves as an enabler for accelerated deployment of solar PV technologies. Ongoing basic research remains necessary for the photovoltaic industry to continue advancing its knowledge and improving lifetime system performance. This document addresses the foundations and reasons why reliability research is crucial to the solar PV industry's continued growth.

After a 6-year decline of the solar photovoltaic market in the European Union, solar deployment started to grow again in 2018. This development is driven by the push towards a faster greenhouse gas reduction needed to achieve the targets of the Paris Agreement. As a consequence, the European Union finally adopted the recast of the Renewable Energy Directive in December 2018<sup>1</sup> and the new (2019 – 2024) Commission in December 2019 launched an European Green Deal<sup>2</sup> to achieve carbon neutrality by 2050 to follow and implement the declaration of the European Parliament on **a climate emergency** on 28th November 2019.

**By 2050**, when the world must have achieved carbon neutrality, the European Technology and Innovation Platform Photovoltaics (ETIP PV) forecasted in the ETIP PV vision for PV<sup>3</sup> that solar PV will supply 70% of the world's electricity generation. **We will use solar PV to move, heat, cool, drive eco-friendly industrial processes and produce fuels.** Solar PV will be deployed everywhere, in systems large and small, designed for productivity and aesthetics as required.

To enable the needed rapid deployment of solar photovoltaics in Europe towards a TW level in the next decade, basic research remains necessary so that the industry can continue advancing its knowledge and improving system performance and lifetime. Basic research, however, is not sufficient to ensure progress and assure quality. Reliability research (typically situated at higher TRL levels) is necessary to ensure that PV power plants deliver the expected performance throughout their entire service life. Ongoing reliability research will ensure that solar plants experience limited component degradation, failures, or system downtime.

<sup>1</sup> Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast), Official Journal of the European Union, L 328/82, 21.12.2018

<sup>2</sup> European Commission Communication, The European Green Deal, COM (2019) 640final, 11 December 2019

<sup>3</sup> <https://etip-pv.eu/publications/etip-pv-publications/download/photovoltaic-solar-energy-big-and-beyond>, Dec 2018

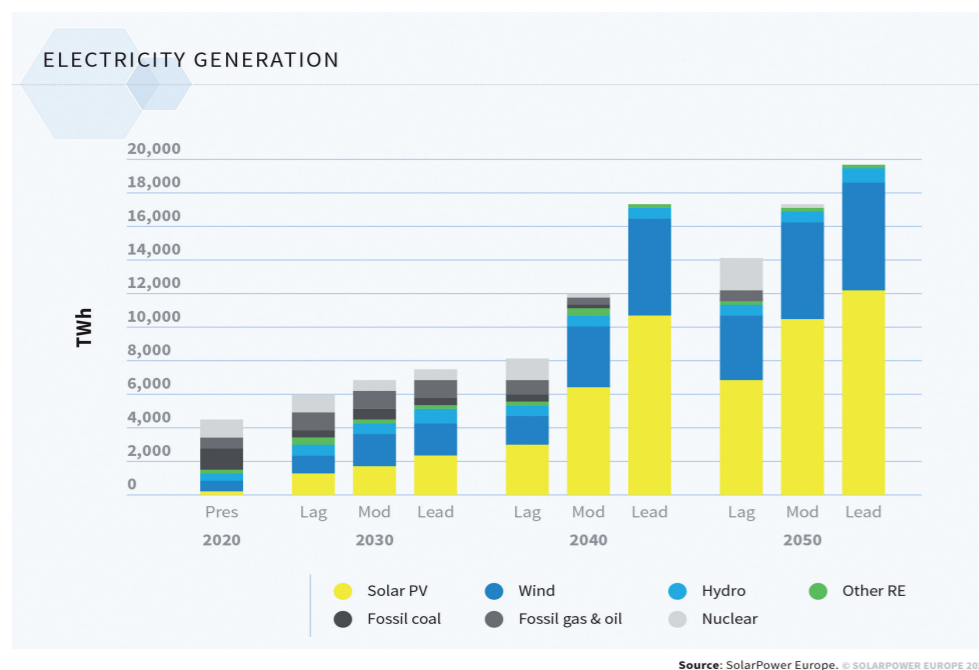
## 1. WHY DO WE NEED ONGOING RESEARCH?

### 1.1 Huge PV deployment volumes and bankable investments

Climate is being destabilized by greenhouse gas emissions, bringing with it more extreme weather events<sup>4</sup>. The unexpected extreme weather of today will be commonplace tomorrow, challenging the reliability of PV components. Europe is undergoing an energy transition, switching from fossil fuels and nuclear power to wind and solar PV as the primary source for electricity generation. In the coming decades, installed PV capacity is expected to rise from 130 GW to the scale of 1 TW. Deployment of PV assets on a terawatt scale requires a significant financial commitment in the range of hundreds of billions euros from utilities, electricity prosumers, energy communities and governments. Given the significant levels of deployment required, and the speed at which the transition is taking place, reliability research must ramp up alongside deployment to ensure stable energy supply at low cost, justifying and assuring bankability of deployed PV systems and PV technology as a whole.

Levelized cost of electricity (LCOE) remains an essential metric in the solar PV industry (as in all other energy sector industries), often used to assess progress in cost, and useful in setting expectations. LCOE not only depends on investments (CAPEX), it also includes operation and maintenance (O&M) costs, and needs the utilization rate (production in kWh/year) as input, which in turn is impacted by service life, PV plant availability and annual degradation rates of the installed PV equipment.

Globally, seventy-nine percent of solar modules are manufactured in China and the countries of Southeast Asia. A significant reliance on imports requires good procedures for quality assurance of components, appropriate to the environment in which they will be installed.



<sup>4</sup> IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

### 1.2 Ongoing technology innovation

PV technology has been undergoing highly dynamic innovation processes for LCOE reduction, which are expected to continue over the next decades. The PV sector is continuously struggling to improve device efficiency and to reduce material and manufacturing cost. Special attention is paid to reducing material consumption (e.g. silicon, silver) and should be paid to replace hazardous materials (e.g. lead) by safe alternatives. Bifacial module technology is quickly entering the market, requiring transparent rear covers and a close look at rear side irradiance. Highly efficient, yet temperature sensitive solar cells call for new, low temperature interconnection technologies. Innovation is also ongoing in the field of PV mounting systems and plant design, e.g. to accommodate bifacial modules or to design agrivoltaic or floating systems. While many innovations follow an incremental approach, disruptive technologies such as tandem devices are being investigated under the assumption that they will substantially exceed single-junction Si efficiencies.

Although historic PV module designs have demonstrated service life potentials beyond 35 years, the sector has learned that every innovation step generates unforeseen reliability risks, not detected by state-of-the-art testing and certification procedures. In the context of innovative materials, it is essential to avoid only screening for known failure modes, that is, those derived from previously used materials, and which do not necessarily cover the failures that occur in new materials. Examples of **novel degradation mechanisms** originating from new technology or materials include PID, LID, LeTID, back-sheet chalking, and thin-film metastabilities.

European PV power plant operators remain uncertain about the materials' quality and the properties needed to ensure it. Though Bill-Of-Materials (BOMs) are becoming more available from manufacturers, these instruments do not provide information about the quality of the components and their link with the total reliability of the device. A small fraction of the solar modules received by the European operators from their Asian suppliers include innate defects due to the **choice of materials** (polymers in particular), which reduce module performance and safety after the first 5-10 years of plant operation. Many European utilities have recorded these defects. These defects impact the performance and service life of the modules and diminish solar electricity production.

Beyond traditional ground-mounted or roof-mounted PV power plants, PV integration into buildings and vehicles is becoming more common. Integrated PV applications include building facades, noise barriers, road surfaces, and floating PV. Integrated applications require unique module designs or materials, and certification and test methods adapted to the new functionalities and environmental challenges. Safety and reliability are crucial for PV modules used in integrated applications.

**Novel tools** and characterization techniques allow more comprehensive approaches to quality assurance in operation and maintenance of PV power plants. The deployment of cost-effective IoT sensors enable module or string level monitoring. Unmanned aerial vehicles combined with multi-spectral analysis provide complete views of large power plants with high spacial resolution.

## 2. WHAT TOPICS NEED TO BE COVERED?

### 2.1 Advancement of type testing and quality check procedures

Type testing standards like IEC 61215 and IEC 61730 are based on experience from former or incumbent technologies. Reliability Research is required for their adaptation to **novel and future technologies**, including heterojunction, passivated contacts or dual junction cell devices, as well as multiwire and shingle interconnection technologies. Reliability Research helps to identify related novel degradation mechanisms, to adapt test schemes correspondingly, and to improve product design. Increasing the knowledge of the properties of new materials and designs with their link to module quality is an important research item and will support overall reliability.

Module type qualification mostly relies on separate tests for different stresses which may not reveal all relevant failure modes. This deficiency is especially critical in case of highly innovative materials and designs. Testing real-size modules in **combined stress** chambers for novel failure modes is a significant improvement of current practices. Reliability research has to investigate the acceleration potential of combined stress testing and to finally translate the relevant stresses into more simple and efficient procedures. Combined stress protocols require collaborative research and knowledge sharing with other industries.

**Highly accelerated stress testing (HAST)** procedures are required to support not only technology development, where it reduces cost and time-to-market, but also for quick quality checks by product off-takers. Reliability Research helps to understand the options and limits of test acceleration.

For the global photovoltaic industry to address the harsher environments of the future, it needs to understand which system components, installation techniques, and O&M practices are the most appropriate. Climatic loads associated with increasingly **extreme weather conditions**, especially

wind speeds and hail, need to be investigated and translated to more demanding module type testing procedures.

Although laboratory record cells efficiencies have been continuously increasing in the last decades together with commercial modules efficiencies, **field performance** has not always been warranted and performance data has rarely been shared with the scientific community. Cost pressure might lead to the development of tests in isolation of use cases which might result in meaningless test sequences for irrelevant failure mechanisms. Accelerated degradation tests on component level need to walk hand-in-hand with performance assessment under relevant climatic conditions, and system level testing including increasingly harsh environments. Soiling, salinity, humidity, high temperatures and high UV exposure may affect different technologies in different ways and accelerate module degradation. Field reliability testing is especially crucial for new concepts and devices where we have little or no experience in yearly performance ratio and extended reliability. Incomplete design verification increases risks of PV plant underperformance significantly. Field reliability research based on high-quality monitoring data is leading to a better understanding of the degradation rates and failure modes leading to the development of preventive maintenance protocols and lower O&M costs, better future control of costs, and thus more accurate LCOE prediction. The reliability of power electronic devices like DC/AC, DC/DC converters and power optimizers as part of PV power plants is crucial. Conceptually, failure rates can be estimated by field data, test data, stress-strength analysis and/or combination of the three methods. For an item operating for a long time, the failure data can be collected and categorized following potential failure mechanisms, and hence, a complete reliability model for a specific operating condition can be provided. This approach requires long term operation of an item

and accurate categorizing the failure cause and mechanisms under given operating conditions. [1] Also, the IEC 61709 published in 2017 [2] provides a guideline to use the failure rate data for predicting the reliability of components considering the temperature cycling in failure rate prediction throughout an annual mission profile. [1] proposes a general reliability prediction approach for power converters according to the failure causes on the most failure prone components.

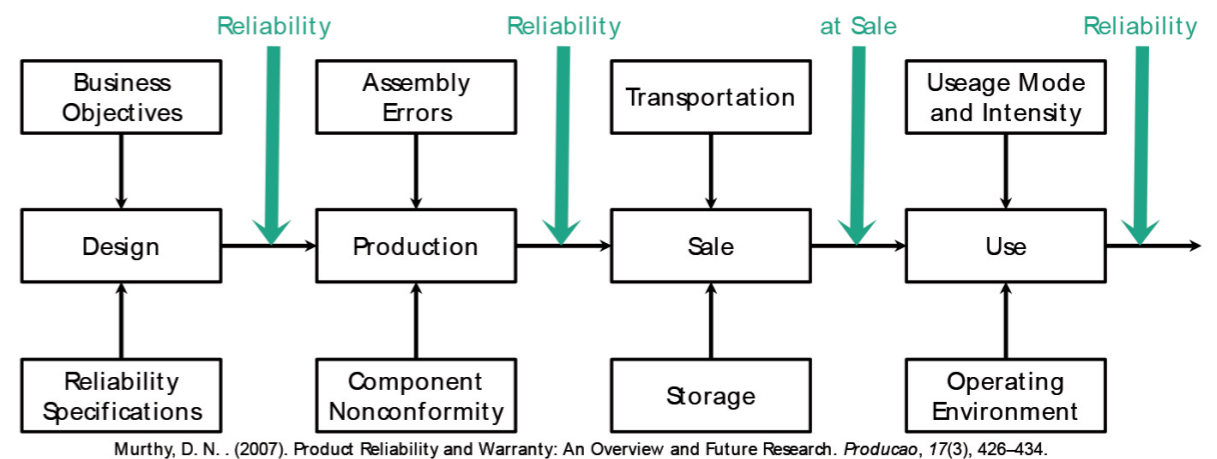
Reliability models can be used for decision making in reliable design, maintenance scheduling, system-level planning, as well as comparing different alternatives such as topologies, control system, modulation scheme, fault tolerant approaches and so on. Finally, different operating and environmental

conditions have an impact on failure rates as well as it causes constant failures or wear-out failures.

**Novel applications** in the context of PV integration come along with specific stress effects. As an example, vehicle, noise barrier and road integration environment subject modules to severe levels of dynamic mechanical stress, while floating PV exposes modules and BOS components to high levels of humidity. For building integration on the other hand, module service life needs to safely achieve levels typical for building materials. Reliability Research needs to investigate the associated material stress and to design and validate adequate accelerated test procedures, based on significant degradation indicators.

### 2.2 Holistic approaches

Today reliability research is often focused on isolated components and often limited to type approval testing. This is somewhat different to other industries where reliability research is ongoing through the lifetime of a product (Figure 1).



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Figure 1: General Industry Approach to Reliability

- [1] Reliability Modeling of Power Electronic Converters: A General Approach, 2019, <https://ieeexplore.ieee.org/document/8769685>
- [2] "IEC 61709 (2017): Electric Components - Reliability - Reference Conditions for Failure Rates and Stress Models for Conversion", 2017.

Each of the stages is associated with some research challenges. However, a reliable system can only be addressed if a **comprehensive quality process** is followed. This is clear when considering a proven design (e.g. according to IEC61215/61730) which is not manufactured appropriately or mishandled during installation – neither will result in a reliable product. A fair share of current quality assurance is based on opinion, while the industry requires consistent, science-based processes. It needs to address not only the PV module, but also the other **balance of system** (BOS) components that affect PV plant performance and safety.

### 2.3 PV plant design

In a PV project the cost of correcting a failure increases exponentially by each step along the value chain from project development to plant operation. Failure prevention instead of correction should be considered as a first mitigation option with an effective risk management strategy during system design and planning. These mitigation options will have costs which need to be counterbalanced by a decrease in operational expenses. Typically, during the design of a PV project, a component qualification process is put in place. This contains compatibility check, risk analysis, supplier audit, and lesson learned.

Mitigation measures must be identified along the PV value chain and assigned to various technical risks. Typical mitigation measures during the design phase are linked to component selection, O&M friendly design, monitoring system design, accessibility of the site, choice of inverter layout and quality check of the input data for yield assessment.

The main research challenges associated to PV plant design are related to (i) the need to create digital twins of PV plants which can be then transferred to the O&M phase, (ii) the introduction of disruptive engineering concepts based on LCOE optimized design, (iii) the reduction of uncertainties related to yield assessments especially in novel emerging PV module technologies.

### 2.4 O&M Support

As the European PV fleet gets older (10+ years), O&M contractors are becoming the main risk managers of PV plants aging and underperformance issues. Field reliability assessment in the operation phase of PV plants for 20-25 years after commissioning has been mainly driven in the past by empirical approaches and field experience. Furthermore, laboratory tests that support field inspections come at very high costs. These costs increase short-term OPEX substantially and are usually prohibitive for O&M contractors in a very competitive market.

In general terms, Reliability Research should be aimed at minimizing or optimizing field operations for lowering OPEX while improving remote failure detection and troubleshooting for increasing energy yield. The digitalization of the entire O&M ecosystem should be at the center of the research challenges, where system simulation (digital twin concept), advanced diagnostic tools and intraday yield forecasting would bridge the gap between the ever-increasing penetration of renewable resources and the grid. Grid integration approaches, such as smart grids, storage, and electric mobility, together with a fully digitalized O&M sector, would pave the path for the energy transition.

Artificial Intelligence (AI) techniques, such as Machine Learning, have started to be applied to the huge amount of monitoring data already available (now considered big data), opening new ways for forecasting approaches, supporting preventive

maintenance through predictive indications with immediate positive impacts on plant downtime and availability. Nevertheless, more powerful on-site and in-situ characterization tools and techniques as well as remote automatic failure detection supported by AI are necessary.

Aerial infrared (IR) thermographic inspections with drones for PV module quality assessment are increasingly used at utility-scale level, because of its high degree of automation, low cost and decent precision. However, future research should be focused on its integration not only with existing SCADA and monitoring systems, but also with the rest of inspection technologies already being widely deployed, such as IV-curve tracing, Electro- and Photoluminescence imaging. It is desirable, therefore, that all these streams of data coming

from the field converge into a unified and centralized digital ecosystem, with AI-analytics at its core, finally closing the gap between field inspections, real power losses and maintenance actions.

Finally, future research should not neglect the important role of field workers and their safety, allowing them to also fully benefit from IoT and industry 4.0 technologies. Field technicians equipped with fully connected smart devices would therefore be able to generate data streams. This stream is fed seamlessly into cloud-based analytic engines and would constantly process and analyze the relevant field data. Those engines would support the decision-making processes necessary to efficiently carry out the maintenance activities that would secure the reliable operation of our PV fleet.





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