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The Path to Future-Proof Photovoltaics in Europe: Current Status and Impact of Technological Innovation on Reliable and Bankable Photovoltaics

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ABSTRACT

With photovoltaics becoming mainstream and hundreds of gigawatts of capacity being added worldwide each year, it is vital that PV systems reliably generate electricity over extended lifetimes while ensuring sustainability from energy, environmental, and investment perspectives. The introduction of novel PV designs and technologies must meet the demand for improved field performance and reliability through continuous innovation, refinement, and adaptation. This study provides an overview of the state of the art and anticipated future developments in PV technology and examines how changes in the technology and design of individual PV components at module level, balance-of-system level, and PV system level can affect the reliability, durability, and energy output of PV installations. We further describe the impact of failures on energy yield, economic viability, and bankability of solar projects, and illustrate how preventive and corrective maintenance, as well as data-driven mitigation measures, can contribute to lifetime extension and strengthen investor confidence. Finally, we present an overview of the key performance indicators, quality assurance measures, and risk profiles that determine the technical and financial viability of PV projects.

1 | Introduction

With photovoltaics (PV) becoming mainstream and hundreds of gigawatts of capacity being added worldwide each year, it is vital that PV systems reliably generate electricity over extended lifetimes while ensuring sustainability from energy, environmental, and investment perspectives [1]. The introduction of novel PV designs and technologies must meet the demands for improved field performance and reliability through continuous innovation, refinement, and deployment. Implementing advanced procedures to extend the lifetime of PV technologies, including a comprehensive lifetime quality assurance policy along the PV value

chain at both component and system levels, naturally introduces additional challenges in terms of bankability, warranties, and contractual frameworks, as well as a need for improved communication standards across the PV value chain.

In this context, the European Technology and Innovation Platform for Photovoltaics (ETIP PV) has developed a Strategic Research and Innovation Agenda (SRIA) for the PV sector, first published in 2022 and updated in 2024 [2]. One of the five key challenges of the SRIA focuses on enhancing the lifetime, reliability, and sustainability of PV technology. The first objective of this challenge addresses sustainable and circular solar PV, while the second

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objective targets reliable and bankable solar PV. The most effective strategy for achieving reliable and bankable PV is to prevent the occurrence of failures and to minimize the impact of failures once they manifest. For new PV projects, emphasis must be placed on the application of novel preventive mitigation measures to reduce the probability of failure during operation. For existing PV projects, advanced data-driven mitigation strategies need to be developed that go beyond the current state-of-the-art concepts of corrective maintenance.

This study is structured into three main chapters addressing reliable PV components, reliable PV systems, and bankable PV projects. Chapter 2 describes the state of the art and expected future improvements in PV technology and examines how changes in the technology and design of individual PV components at module level, balance-of-system (BOS) level, and PV system level can affect the reliability, durability, and energy output of PV systems. Chapter 3 analyses the impact of failures on energy yield, economic viability, and the bankability of solar projects, and illustrates how preventive and corrective maintenance, as well as data-driven mitigation measures, can contribute to lifetime extension and enhanced investor confidence. Chapter 4 provides an overview of the key performance indicators, quality assurance measures, and risk profiles that influence the technical and financial viability of PV projects.

At the end of each chapter, the paper presents recommendations and perspectives on optimizing manufacturing processes, standardizing methodologies, and implementing quality assurance and quality control practices to mitigate energy losses and field issues.

2 | Reliable PV Components

Reliable PV components are necessary to deploy reliable PV systems at large scale and meet global decarbonization goals. Reliability of PV components is key to build confidence in PV, reduce real and perceived risks, enable access to finance, secure low risk procurement, and ultimately lead to a wider and faster deployment of PV.

According to the 16th Edition of the ITRPV report [3], PV module performance warranty lifetimes are shifting from 25 to 30 years and product warranties from 15 to 17 years by 2034. Inverter lifetimes are deemed to remain at 15 years. Nonetheless, common expected project and module lifetimes are expected to be +30 years. Longer warranties are an industry demand which is obviously not supported by direct field experience. For this reason, it is important to realign lifetime targets (proven with durability and reliability indoor and outdoor testing) with warranties. The Strategic Research and Innovation Agenda on Photovoltaics (SRIA) [2] calls for 40-year lifetimes by 2035, with lifetime defined as the time in which the initial performance is reduced to 80% or safety is compromised.

In addition to gradual irreversible degradation, which is key to determining long-term effects and operational lifetime, a system owner focuses also on the failure rates which lead to module replacements at all phases of the project life and which can

be due to intrinsic or extrinsic factors. A study from the International Energy Agency (IEA) PVPS's Assessment of PV Module Failures in the Field [4] exemplifies the occurrence of failures from the field over the years of PV plant operation, showing an increase of the total failures in year 7, which challenges the conventional assumption of a bathtub failure rate model for PV modules, wherein failure rates decrease after a few years and then stabilize. Inverters, on the other hand, require higher replacement rates due to a wide variety of failures. Since PV modules are currently non-serviceable, minimizing failure events requires dedicated procurement of reliable and durable PV modules.

Levelized cost of electricity (LCOE) and internal rate return (IRR) are strongly impacted by the selection of standard, reliable or durable PV components. Albeit cost reductions in PV modules have been the main driving factor for the sector, extended lifetimes and lower degradation rates and O&M costs have also a strong impact on LCOE and IRR.

The parameter with the largest impact on the LCOE is the cost of capital. Risk reduction in PV projects will lead to easy access to capital and thus to lower WACC or to projects with similar WACC. Technical parameters will thus become more important for the comparison of PV projects; the variation of technical parameters becomes essential in the benchmarking of LCOE [5]. It is in this context that the competitiveness of PV in the future will be (i) closely linked to the uncertainty and variability of the input parameter determining the initial yield value and (ii) cost effectiveness and improvements of parameters related to the downstream sector of the PV value chain will have an impact. Quality along the whole value chain will thus become essential to match the expectations generated in the Yield Assessment.

As seen in Figure 1, parameters like lifetime, degradation or Performance Loss Rate, Performance Ratio, and Operational Expenditures (OPEX) can have an overall impact on the LCOE which can be as high as 100% (doubling of LCOE) [5].

2.1 | PV Module Technologies

PV modules are central to photovoltaic systems and a major focus of innovation. From 2010 to 2025, average efficiencies rose from 14.7% to 22.6%, module power increased from 240 Wp to over 700 Wp, and prices fell from 2.24 USD to 0.08 USD per Wp [3]. While efficiency and cost remain primary drivers, recent efforts also target extended lifetimes and improved sustainability [6, 7].

However, the rapid evolution of PV technologies, combined with accelerated deployment, means that many modules in the field today rely on materials with limited long-term performance data, potentially raising new reliability risks [8, 9]. In the past, degradation mechanisms such as PID, LeTID, and backsheet cracking emerged unexpectedly after just a few years in operation. More recently, UV-induced degradation in TOPCon and SHJ cells and a rise in glass breakage have prompted revisions to standards (e.g., IEC 61215, IEC 63209) and the development of new laboratory test protocols. To manage risks from accelerated product cycles, intensified research is needed to improve both reliability testing and reliability-oriented design.

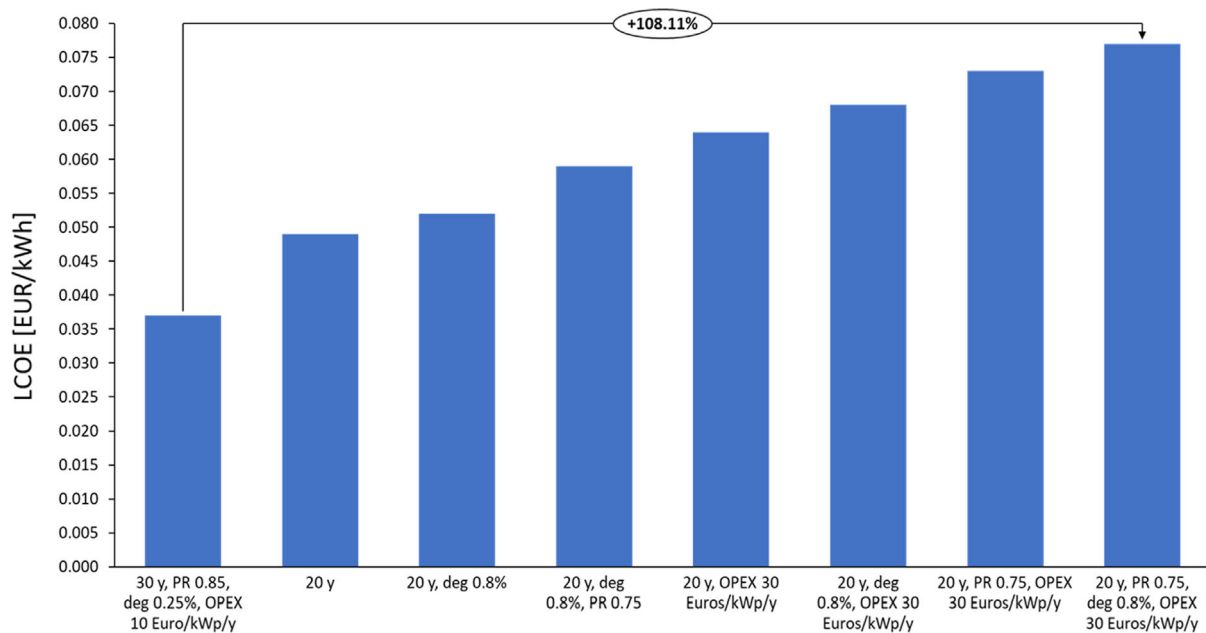


FIGURE 1 | Impact of technical parameters during the operational phase on the LCOE Reproduced with permission [5]. Copyright 2020, IEA PVPS.

TABLE 1 | Summary of key changes in PV module technology (2010–2025).

Component	Key changes	Drivers	Challenges/risks
Wafers	Size: M0 → M10/G12 Thickness: 180 μm → <140 μm	Cost reduction, higher power output	Mechanical fragility, microcracks
Cells	Al-BSF → PERC (p-type) → TOPCon/SHJ/BC (n-type)	Higher efficiency, LID/LeTID mitigation	UVID, PID corrosion
Interconnects	Multi/zero busbar, shingled, foil-based	Reduced resistance, lower silver use	Thermomechanical stress at joints, solder/adhesive fatigue
Module Size	1.6 m ² → >2.5 m ²	Lower BOS and transport cost	Handling, higher wind/snow deflection, glass breakage
Glass/Backsheet	Thinner glass, double-glass, PFAS-free backsheets	Bifacial designs, weight/cost savings, regulatory compliance	Glass tempering limitations, cracking, electrical safety
Encapsulants	EVA → POE, EPE	Better PID resistance, lower WVTR	Higher cost, shorter field records for long-term durability
Manufacturing	Rapid scaling, digital tools, gigawatt-scale Smart fabs	High yield, low cost, automation	Ramp-up defects, quality variability

An overview of the main technological shifts and associated reliability challenges is provided in Table 1.

2.1.1 | Wafer-Level Changes

The past decade has seen a shift from M0 wafers (156 × 156 mm²) to larger formats like M10 (182 mm) and G12 (210 mm), driven by cost reduction and higher module power. At the same time, wafer thicknesses have dropped from ~180 μm to ~130–140 μm to reduce polysilicon use without compromising efficiency.

However, thinner and larger wafers are more prone to damage during manufacturing and operation due to increased thermomechanical stress [10–12]. Finite element modeling and careful process testing (e.g., electroluminescence) are very valuable tools to assess and prevent microcrack formation and optimize module

robustness [13]. Large wafers are often combined with cell cutting to reduce resistance losses and cell bowing, as well as improving shading tolerance. While half-cut cells offer greater resistance to cracks, the cutting process can introduce defects if not optimized [14].

2.1.2 | Changes in Cell Technologies

Monocrystalline p-type PERC cells have dominated over the last decade, replacing Al-BSF. Since 2020, n-type silicon technologies—mainly tunnel oxide passivated contact (TOPCon), heterojunction technology (SHJ) in bifacial or back-contact (BC) configuration—have gained ground, now representing over 70% of the market thanks to improved efficiency and energy yield, combined with falling costs. These new architectures offer excellent surface passivation, and well suited for use in combination with

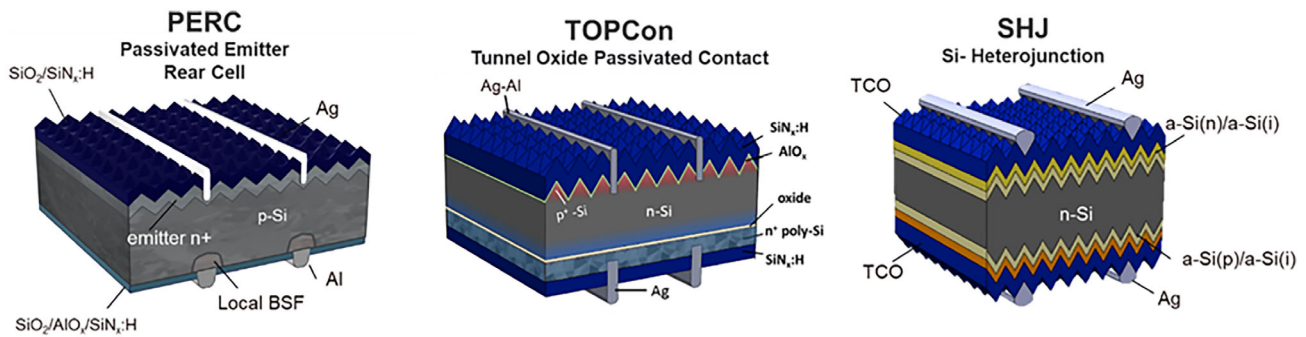


FIGURE 2 | Representation of bifacial PERC, TOPCon, and SHJ devices Reproduced with permission [15]. Copyright 2022, Institution of Engineering and Technology.

thin wafers, which allows bulk recombination minimization. Figure 2 illustrates the main bifacial architectures [15].

Unlike p-type PERC cells, n-type designs eliminate light-induced degradation (LID) by avoiding BO complex formation. Light and elevated temperature-induced degradation (LeTID) is also largely mitigated through lower hydrogen content and optimized firing conditions [16].

However, n-type cells can still be susceptible to potential-induced degradation (PID). For TOPCon, PID-p (polarization) is particularly relevant, as charge accumulation at the Si/dielectric interface can increase recombination losses—though this effect is usually reversible under illumination or heat [17]. In SHJ cells, PID-c (corrosion) can occur irreversibly at the transparent conductive oxides (TCOs). While PID-s (shunting) is less frequent with modern materials, it can still occur due to ion migration from glass through the encapsulant. PID effects can impact both front and rear surfaces, especially in bifacial designs, yet current standards (e.g., IEC 62804) primarily address front-side PID, highlighting the need for updated testing protocols [18].

In addition, some of the very thin surface layers in TOPCon and SHJ structures can be in some cases more sensitive to external stressors [19], such as UV exposure [20], humidity, or contamination [21–23]. UV-induced degradation has been observed in SHJ and TOPCon cells, prompting the development of specific test sequences [20, 24].

2.1.3 | Changes in Interconnect Technologies

The industry has witnessed significant advances in interconnect technologies during the last years. Module total area efficiencies have increased by reducing or eliminating the gap between cells and by increasing the number of busbars, to reduce series resistance losses and thermomechanical stress on the cells, as well as increase light capture.

Multi-busbar or zero-busbar designs, which employ foil-based wiring meshes, enhance current collection and reduce silver consumption [25, 26]. These multipoint connections also improve mechanical resilience by ensuring cracked cell fragments remain electrically connected. Cell gaps have progressively shrunk, with some modules using shingled designs where cells overlap at the edges. This maximizes active area and offers appealing aesthetics,

especially for BIPV, though local mechanical stress near joints can be a reliability concern [27].

In parallel, new solder materials and processes have been introduced, particularly for lead-free or low-temperature processes required by SHJ cells. Electrically conductive adhesives (ECAs) and low-temp solders like SnBi or SnIn help meet these requirements but present challenges, including lower fatigue resistance [28, 29] and potential adhesive failure [30]. Material compatibility has become increasingly critical. For example, certain soldering fluxes, when used with specific cell metallization like SHJ or TOPCon, have been linked to corrosion or other failures [21]. This underlines the need for rigorous testing of full material stacks—and not just individual components.

2.1.4 | Module-Level Changes

Module formats have grown significantly in recent years, with areas increasing from $\sim 1.6 \text{ m}^2$ to over 2.5 m^2 . Larger modules reduce manufacturing, transport, and BOS costs, but can also introduce certain challenges: they are more vulnerable to mechanical stress during transport [31], installation, or operation (e.g., when exposed to wind and snow loads), especially when combined with thinner glass and narrower frames. Ensuring robustness requires careful structural design and adapted testing.

Material changes at the module stack level have also accelerated. The adoption of double-glass designs—often with thinner glass to reduce weight and cost—has become widespread with the rise of bifacial modules [32]. However, thinner glass (especially $< 3 \text{ mm}$) is more prone to breakage and often cannot be fully tempered, leading to reduced mechanical performance [33, 34].

Backsheet materials have diversified beyond the classic fluoropolymer/PET structures, in pursuit of cost reduction or PFAS-free alternatives [35]. New non-fluoropolymer backsheets and coextruded designs require careful qualification [36] to ensure long-term durability and electrical safety, as cracking or chalking may not initially affect performance but can pose safety hazards at a later stage.

Encapsulants have also evolved. While EVA remains dominant, white EVA is now used to enhance reflectivity. Polyolefin elastomers (POE) offer lower conductivity and improved moisture resistance, reducing the risk of PID and corrosion [37–39].

However, POE is more expensive and has a shorter field history, which increases uncertainty about long-term reliability. Many modules combine EVA and POE (e.g., EPE coextruded films), but such hybrids also require rigorous testing and long-term exposure to validate durability.

Along with the development of encapsulants, the combination with cell architectures like that of TOPCON can lead accelerated degradation due to EVA generated contaminants and type of solder flux for SHJ cell architectures [40, 41]. These combinations require smart approaches to reliability testing for these technologies installed in tropical or Mediterranean climates.

2.1.5 | Changes at the Manufacturing Level

The PV industry's shift to gigawatt-scale production and rapid deployment of new technologies (e.g., TOPCon, SHJ, xBC) has introduced steep learning curves in manufacturing. New lines must reach high yield quickly, often while adapting to unproven processes with tighter tolerances. This increases the risk of defects—such as microcracks, frame distortion, or material incompatibility—especially during ramp-up phases.

While quality guidelines like IEC 62941 exist, implementation varies across factories. Defects may result from poor calibration, inadequate maintenance, inconsistent quality assurance, or improper material handling. These issues can trigger both early and late failures: delamination or structural defects often stem from lamination errors, while long-term issues like discoloration or encapsulant degradation are tied to poor material selection.

As global manufacturing expands, maintaining consistent quality will depend on advanced automation, improved traceability, and digital tools—such as real-time monitoring, predictive maintenance, and digital twins—to reduce variability and ensure long-term module reliability [42].

2.1.6 | Perspectives

Reliability and durability are essential to ensure the long-term performance and bankability of PV systems, especially as technologies evolve and deployment expands into diverse applications like agrivoltaics and floating PV. Predicting aging behavior remains a major challenge for new technologies, particularly those at low TRL, such as perovskite-based modules. To bridge the gap between lab innovation and field performance, accelerated indoor tests are continuously refined to study failure mechanisms, even if they do not fully replicate real-world conditions. These efforts inform design and manufacturing improvements and help align reliability with evolving field conditions.

New quality rating frameworks are emerging to assess module lifetime potential based on testing depth, traceability, and manufacturing quality control [43, 44]. These classifications will support procurement decisions and help differentiate between low-cost, short-lifetime modules and those designed for demanding environments. As climate-related stressors intensify and system diversity increases, material compatibility and integration will become even more critical. Small variations in encapsulants, backsheets, or interconnect materials can strongly affect long-term performance. Ensuring reliability will therefore depend

on coordinated advances in testing protocols, digitalization, and quality management across the value chain.

Looking ahead, ensuring the long-term reliability of PV modules will require adaptive strategies that anticipate emerging challenges linked to new technological developments. As deployment scales rapidly, the development of new multistress testing procedures and advanced modeling techniques will be crucial to better understand the physics of degradation modes, enabling more accurate predictions of long-term performance. Digital tools will play a pivotal role in optimizing product quality in manufacturing as well as supporting the design and development phases, while quality-rating classifications based on material traceability, testing procedures, and factory audits will become increasingly vital for guiding procurement decisions and managing risk across the supply chain. Ultimately, continued progress to reduce quality risks and maximize service lifetime will depend on the alignment of innovation, standardization, and data-driven strategies. This approach is reflected in the Strategic Research and Innovation Agenda (SRIA) for Photovoltaics, particularly under Challenge 2 – Objective 2, which calls for enhanced quality assurance, long-term reliability assessment, and traceability measures to ensure the bankability of solar PV technologies across diverse applications and operating conditions [2].

2.2 | Inverters and BOS

As noted in Section 2.1. PV Module Technologies, string inverters like PV modules have grown in their kVA rating in the last 10 years, going from 60 kVA to ~350 kVA during this period [45, 46]. These advancements alongside PV module increases in efficiency and wattage have allowed significant reductions in Levelized Cost of Electricity (LCOE). Inverters also typically come with warranty lifetimes from 5 to 15 years. Inverters need to withstand adverse conditions (climate, temperature, stresses from grid) and adverse events (severe weather, O&M damage, installation damage). An integral part of the LCOE is also the operational cost and, in turn, replacement rate of these components. Previous studies reported from breakdown of operation-and-maintenance events from PV operators that the inverter constitutes 43%–70% of the service calls [47]. The EU project TRUST-PV reported that 62.5% reported failures of all failure events during the operational life of a PV system based on 35,000 maintenance tickets [48]. These values are updated for more than 250,000 maintenance tickets and presented in Section 3. Estimated lifetimes of inverters can deviate up to 54% because of PV panel degradation in different climates [49]. Inverters see a higher frequency to derate at high temperature and high elevation operation. Inverters cooling ability is reduced at lower air densities and higher temperatures, which necessitate a reduction in waste heat and thus power derate [50].

The solar industry has seen a significant shift in DC:AC ratios, particularly in utility-scale applications. Years ago, PV plants were designed with modest DC:AC ratios, typically between 1.05 and 1.1. In more recent years, DC:AC ratios for both C&I and utility scale plants have increased from anywhere between 1.5–1.8 DC:AC [51]. Bollinger et al. reported for the USA that in 2023, the median inverter loading ratio was 1.34, and was higher for fixed-tilt installations (1.38) than for tracking projects

(1.32) [52]. This trend is driven by the decreasing cost of PV modules relative to other system components, making it economically viable to install more DC capacity per inverter.

Increasing AC:DC ratio can introduce issues in inverter reliability, for example, due to AC:DC clipping, curtailment, and masking of other effects (i.e., soiling) [53]. Clipping occurs under high irradiance conditions when DC power input from the array generates an AC power output exceeding the AC power rating of the inverter. Curtailment occurs when a solar PV system generates more electricity than the local grid or infrastructure can effectively handle. To reduce reliability issues, modern inverters incorporate smart clipping, enhanced current handling, and advanced MPPT algorithms. These new features are important as an inverter responding to minutes if not seconds into clipping and curtailment regimes may lead to malfunctioning of that component [54]. Additionally, initial preliminary studies indicate significantly uniform elevated temperatures and checkboard voltage patterns in PV modules if arrays are operated below Maximum Point (MPP) which impacts module lifetime & degradation rates [55]. It is important to note that improper consideration of albedo and AC:DC ratios may negate the benefits of bifacial modules [56]. Inverter failures all in all are the main cause of large fluctuations in availability and, in turn, performance ratio of solar plants.

Raptor maps in the analysis of all the collected data present in their platform, report a % of non-PV module related power losses around 5% in 2024 (inverter, combiner box, tracker misalignment, vegetation, and others), with an increasing trend compared to previous years [57].

Transformer degradation and loss of life heavily depends on the load on the transformer by the PV system [58]. In general, this depends on the transformer sizing, harmonics caused by inverters, on-load tap changer, and reversal of active power on the loss of life and degradation. Transformers are designed for a more constant loading operation, wherein PV system requires daily switching, partially because of curtailment. It is important to note that losses have a quadratic time varying relationship with current. Another factor that impacts transformer lifetime and degradation is clipping at the Point of Interconnection, and the AC losses attributed to it. Although the problems are known, to the best of our knowledge, there is no recent scientific literature available for transformers used in utility scale PV systems. The H2020 project TRUST-PV studied the phenomenon, but the results obtained were not statistically relevant, and thus results were not published [59]. With this study, we urge the community to analyze transformer related issues and report findings when available.

2.3 | Estimation and Modeling of Component Degradation

PV systems are designed to have 25-to-30-year lifetimes to meet the developer and system owner business cases [60]. SRIA ambitions to achieve 40 years or more lifetimes require a new approach to ensure durable, resilient and reliable systems that last that long. To achieve these goals, replacement rates and degradation rates of not only PV modules and inverters, but also

transformers in a variety of different applications (Agri-PV, Floating, Rooftop and Ground) and distinct climates (arid, tropical, coastal, temperate, continental) must be understood.

Surveying current challenges in the development, construction and operation of a PV system can help to design reliable, durable, and resilient systems. KWh Analytics 2024 Solar Risk Assessment report [61] addresses a concern that solar assets in the USA are broadly performing below expectations, indicating that 7%–15% are under performing due to overly optimistic P50 yield assumptions, high replacement rates of components, soiling, and poor maintenance. According to the Raptor Maps 2023 global solar report, the solar industry lost \$2.5 billion annually due to equipment underperformance [57]. This value is bound to grow exponentially with exponential growth, and the updated 2025 global solar report shows a figure of 5720 USD/MW per year (214% increase over the past 5 years) of potential average revenue loss which can be roughly translated into 11 billion USD of global revenue losses in 2024 (considering 2 TW of global capacity).

2.3.1 | Module Challenges for Degradation Estimation

Degradation is stipulated to be % annual loss as in accordance with warranty conditions named by PV module manufacturers [60]. The 16th Edition of the ITRPV 2025 report [3] shows the initial degradation warranties will shift from 2% to 1% in 2026. Annual degradation is expected to be reduced slightly from 0.45% continuously to below 0.4% within the next 10 years.

Accelerated lifetime tests like that of IEC 63216 (High Temperature), IEC 62804 (PID), IEC 63422 (LeTID), IEC 60068 (Sand Abrasion), IEC 62938 (snow load), and IEC 62309 (standardized test scheme for accelerated lifetime testing). However, accelerated tests are not universally considered the best benchmark to replicate real conditions [42].

Prescribed values by independent ISO17025 labs measuring PV module power at least every 5 years in distinct geographic and climatic conditions show that these are typically 0.5%–0.6% per year (median value), and 0.8%–0.9% per year mean value in a linear degradation [62]. Though these values may be skew due to them not considering initial measurement uncertainty of 3%. Moreover, the likelihood of module mismatch in an array may also impact series resistance, which may further lead to heat dissipation because of negative deviations in power as measured by Fraunhofer ISE.

Module lifetimes may also vary per climate, wherein environmental factors like the wind and/or snow load, bird dropping stones on modules causing glass breakage, rodents eating DC cables, storms, hailstorms, and lightning strikes can impact failure modes and in turn replacement rates. The sixth assessment report by IPCC report indicates a realistic increase in both the frequency and intensity of extreme weather events and in turn the occurrence of failures due to these events. The NREL DuraMAT FY 2023 Annual Report [63] indicates that dependent on interconnection, BOM thicknesses and types, frame sizes may impact the sustainability/replacement rate of PV modules under high wind load or hail prone locations and should be considered part of the site consideration when designing a PV system. The market trend for thinner semi-tempered glass and thinner frames

is addressed as a concern for locations where these weather events are common [34]. Though smart stowing of tracker systems can to an extent mitigate hail damage as proposed by the VDE best practices for hail stow.

Accounts by independent engineers and IEC 60364-7-712 (standard for design, construction, and verification of electrical installations), IEC 61724, and IEC 62446 inspectors indicate that poor handling, improper installation, and below standard maintenance are a main source of early lifetime failures and fire hazards. Smart implementation of the Solar Power Europe EPC and O&M best practices intends to tackle these challenges alongside these norms though is a constant work in progress.

2.3.2 | PV Module Rd Modeling

The degradation rate of a PV module quantifies the long-term decline in its power output over time. The degradation rate is often provided by manufacturers in PV module datasheets and is commonly used in estimating the system's lifetime energy yield. However, findings from IEA-PVPS Task 13 highlight that Rd is a major source of uncertainty in long-term energy yield predictions and LCOE [5]. This is primarily due to significant discrepancies observed between field-derived Rd and those stated by manufacturers. These deviations have been linked to various influencing factors, including climatic impact, PV installation parameters, and evolving applications such as building-integrated PV (BIPV) and floating PV systems. Such variations introduce new stressors which affect PV module degradation rates. Consequently, manufacturer-provided degradation rates require context-specific adjustment to remain valid across different environments and installation conditions.

Although there is currently no standardized framework for correcting Rd values to account for these variations, several researchers have proposed climate-adaptive degradation models. For instance, Bala et al. [64] and Kaaya et al. [65] have developed physics-based models to quantify the impact of combined climatic stressors (e.g., static and cyclic module temperature, ultraviolet radiation, and relative humidity) on power degradation. These models offer valuable insight into how local environmental conditions influence PV performance degradation and can help identify dominant degradation mechanisms.

Moreover, to address performance variations related to installation parameters (e.g., tilt angle, elevation, and azimuth) and emerging PV applications (e.g., building-integrated PV systems), degradation models have been integrated into bottom-up, physics-based energy yield simulation frameworks. A notable example is the TRUST-PV project [66], where such models were embedded within IMEC's patented simulation framework [67, 68].

This framework incorporates key parameters related to PV system design, module technology, and the optical and thermal properties of module components to simulate module temperature. In addition, it includes a ray-tracing engine that enables precise estimation of plane-of-array (POA) irradiance, from which the ultraviolet (UV) dose incident on the PV modules can be derived. Beyond reducing the overall uncertainty in degradation rate prediction, the physics-based nature of the

framework enables “what-if” simulations to assess the reliability implications of design choices, installation conditions, and application-specific scenarios.

For example, Hameed et al. [69] utilized the integrated simulation framework to explore how variations in PV system design parameters—such as tilt angle, inter-row distance, azimuth orientation, and elevation—affect system performance, reliability, cost, and environmental impact. The analysis revealed that strategic optimization of these design parameters can prolong the operational lifetime of PV module by 1–4 years, decrease the LCOE by as much as 19%, and cut greenhouse gas emissions by 8%–17%. These insights highlight the critical role of incorporating reliability-driven design strategies in PV system planning and deployment. In a related study, Kaaya et al. [70] combined the framework with experimental measurements to evaluate thermal behavior in building-integrated PV (BIPV) systems. They found that BIPV installations with closed air cavities generally operate at significantly higher temperatures than those with open cavities, with average temperature differences reaching up to 15°C, depending on the climate. Simulations showed that this temperature increase could reduce system lifetime by as much as 10 years, varying with the climatic zone in which the BIPV system is deployed.

2.3.3 | Climate Impact on Degradation Rates

Leveraging climate data such as ERA5 reanalysis data offers a promising approach to better understand, model, and ultimately predict PV degradation mechanisms as observed in the field. Thermomechanical degradation is a significant factor, especially in high-irradiation regions, and highlights a correlation between degradation rates and the Köppen–Geiger–Photovoltaic (KGPV) climate classification. Findings suggest that long-term PV performance will be increasingly impacted by climate change, particularly because of global warming. Figure 3 shows the results of the applied modeling of degradations mechanisms as described in the sections above. Recently developed global degradation maps offer insights into climate-induced stress on PV systems in Europe. It may serve as a risk assessment tool rather than a precise predictive model due to uncertainties in real-world degradation rates.

Various research activities are focused on improving the thermal management of PV modules. Notable example is the use of optical filters that can yield operating temperature reduction of a range of 2–2.5°. The authors report that in a single year, the optical loss produced by the filter is not compensated via temperature reduction. However, improvements in the annual degradation rate show that in Singapore, the overall effect of the filter on the lifetime DC energy yield is positive [71].

3 | Reliable PV Systems

3.1 | PV System Degradation Modeling

The energy output and performance of PV systems is known to change over time due to various factors, including PV module degradation, soiling, snow cover, inverter malfunction, clipping,

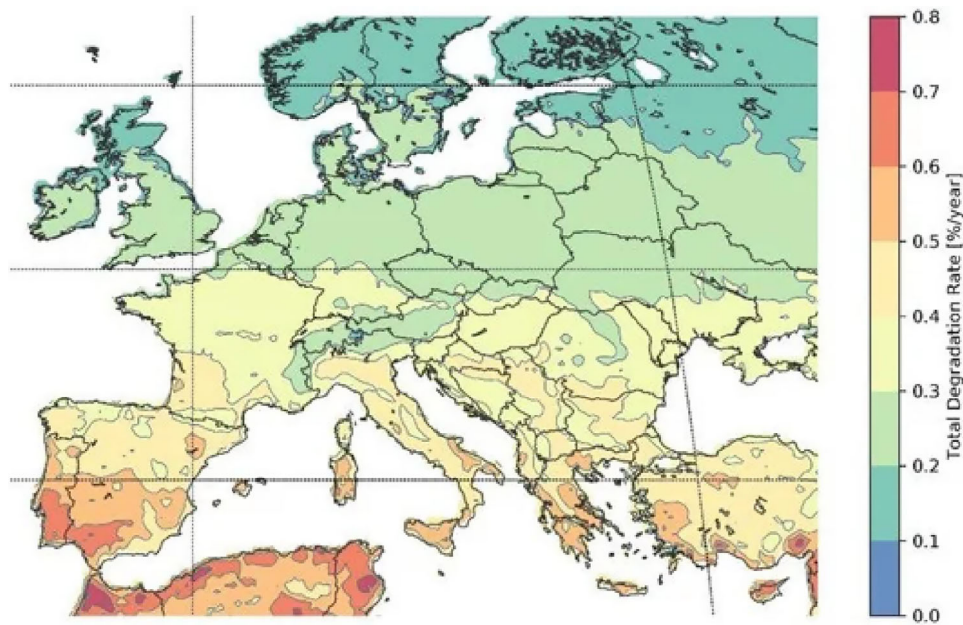


FIGURE 3 | European categorization of total degradation rate based on temperature, humidity, and UV irradiance for a specific monocrystalline silicon PV module. Reproduced with permission. Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules.

and system downtime. The performance loss rate (PLR) quantifies the overall reduction in system performance, encompassing all degradation mechanisms together with other performance impacting issues, and is distinct from the module degradation rate, (Rd). Instead, the Rd refers solely to the decline in module power output driven by appearing degradation modes, many of them mentioned in Figure 4. The relation between PLR and Rd is depicted in Figure 4. Both parameters describe a performance change over time, typically expressed as a percentage per year. Modeling performance losses and degradation in PV systems plays an important role in predicting and assessing the long-term energy generation, informing maintenance strategies and evaluating financial returns.

PLR values are typically calculated using a top-down approach based on measured performance data, whereas degradation rates are often modeled using a bottom-up approach that considers climate-specific stressors to estimate long-term,

degradation-driven losses in PV plant output. The next two sections describe recent advancements in both fields.

3.2 | PV System PLR Estimation

PV system PLR is evaluated from field data using statistical and machine learning models [73]. Inconsistencies in PLR calculation methodologies have been highlighted in several studies. For example, Makrides et al. [74] and Lindig et al. [75] demonstrated that the choice of analysis method significantly affects the absolute PLR values obtained, even when applied to identical datasets. These discrepancies arise not only from the selection of PLR models but also from the absence of a standardized data handling and analysis pipeline. To address this gap, the IEA PVPS Task 13 working group initiated an international framework aimed at harmonizing PLR assessment procedures [76]. This framework recommends a structured

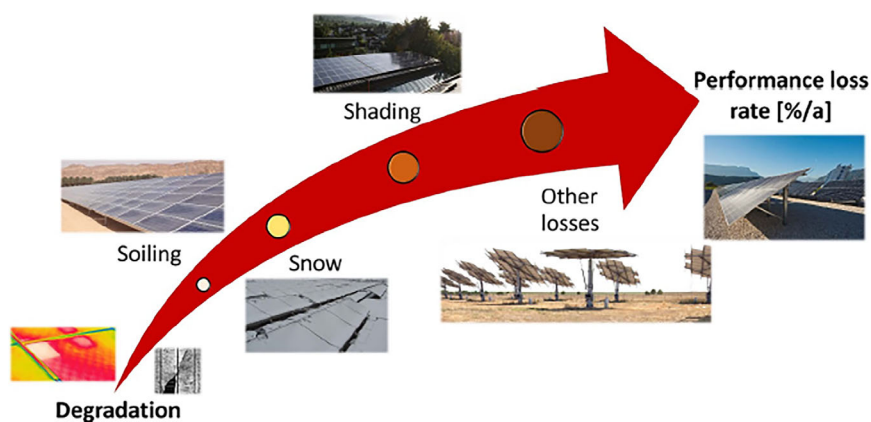


FIGURE 4 | Relation between degradation and performance loss rate (expressed in percentage per year (%/a), system-level PLR captures both irreversible degradation and reversible losses). Reproduced with permission [72]. Published in Progress in Energy under Open Access CC BY 4.0.

sequence of steps, including: (a) input data quality assessment, (b) data cleaning and filtering, (c) performance metric selection together with corrections and aggregation, (d) possible time series feature corrections, and (e) the actual PLR calculation using statistical models [76]. Despite this initiative, improving the accuracy and reproducibility of PLR estimations across varying technologies, PV applications, and climate conditions remains an open area of research. This ongoing effort includes the development of best practices [72], novel methodologies [77], and software platforms [78] for robust PLR extraction. Ultimately, establishing industry-wide consensus and standardized methodologies for extracting PLR values from field data is essential for advancing a reliable and bankable PV sector.

3.3 | Impact of Failures

As PV deployment continues its exponential growth trajectory, reliability and performance assurance have become increasingly critical. Technical failures in PV systems directly impact energy yield, economic viability, and ultimately the bankability of solar projects. While the industry has witnessed a substantial reduction in capital expenditure (CAPEX) costs over the past decade, this has simultaneously placed greater pressure on operational expenditure (OPEX) budgets, as these are often calculated as a percentage of installation costs. This economic reality creates a challenging environment where maximum reliability must be achieved with increasingly constrained maintenance resources.

Beyond economic considerations, system availability has become a critical metric for grid operators and energy traders, with failures potentially affecting grid stability and energy market positions. Safety concerns have also gained prominence as aging systems present new hazards, requiring advanced inspection protocols and risk mitigation strategies to protect both personnel and equipment throughout the system's lifetime.

3.3.1 | Frequency of Failure Statistics

Analyzing failure statistics gives interesting insights into PV systems' reliability and allows us to identify the most critical points of failure. Lindig et al. [48] analyzed over 35,000 O&M tickets to categorize failure frequency by affected component, subcomponent, and event. The TRUST-PV Risk Matrix [79] guides this standardization of failure classification, making it easier to compare issues across different PV sites operated by different technicians.

The study [48] found that inverter-related issues accounted for 62.5% of all reported failures, with the most frequent failure modes being complete inverter shutdowns ("Off" – 22% of all tickets), communication errors, and loss of generation. Communication and monitoring system failures represent the second largest category (13.4%), followed by system-level issues (12.3%). However, a potential bias exists in failure statistics due to the way failures are recorded—automated monitoring systems may prioritize inverter faults over less detectable module degradation. An extended statistical assessment of a dataset of 250 000 O&M tickets further supports this observation.

The results shown in Figure 5 confirm the high representation of tickets concerning the inverter. Underperformance reported by the inverter is with almost 80 000 tickets the most common issue followed by approximately 40 000 tickets related to data communication issues or transmission errors of the monitoring system. Only a small part of the overall batch is reported for the modules, despite their critical importance to system performance.

Analysis of module failures reveals distinct patterns following severe weather events such as hailstorms [80] and high winds. Such events can result in immediate glass breakage, in particular for PV modules with low front glass thickness [81] but also cause microcracks that remain invisible without advanced inspection techniques, leading to accelerated degradation rates and severe safety risks due to electrical hazards. This highlights a significant gap in standard monitoring approaches, as these latent damages

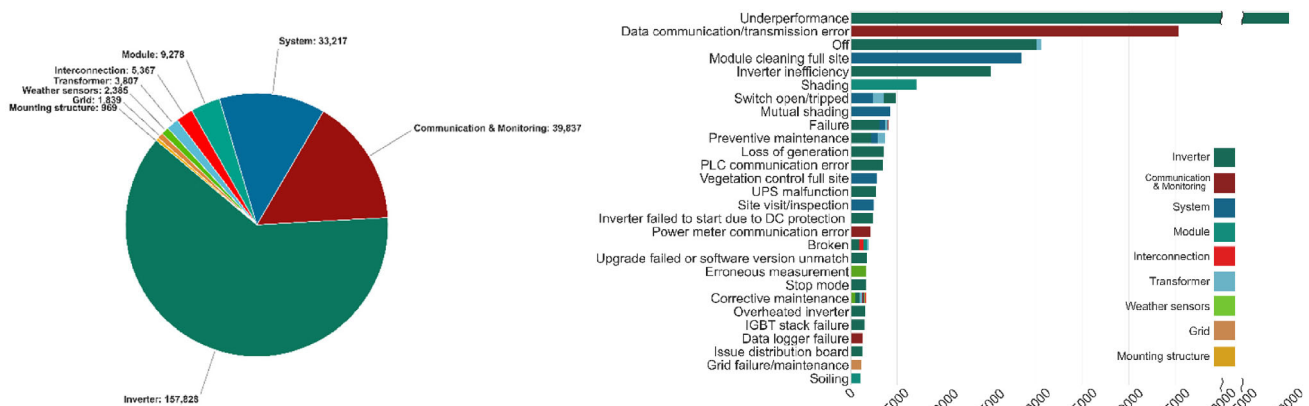


FIGURE 5 | Failure statistics in PV systems based on O&M ticket analysis. The graph on the left shows the distribution of the tickets by PV system component. The analysis demonstrates the predominance of inverter-related issues (62.0%) and communication and monitoring problems (15.7%). The graph on the right ranks the 20 most frequent events recorded across all components, with each event color-coded by component type. The predominance of inverter-related issues is visually highlighted by the dark green color in both graphs. These updated results build upon the original data set presented by Lindig et al. [48], now extended with a significantly larger ticket database.

often manifest as performance issues months after the precipitating event.

Herz et al. [82] identified module failures as a significant contributor to system underperformance, especially due to potential-induced degradation (PID), cracked cells, and backsheet deterioration. The study highlighted the necessity of enhanced material selection and quality control in reducing these failures. With more advanced inspection methods like luminescence inspection [83], NIR-spectroscopy [84], or I–V curve tracing, it is possible to reach a conclusive diagnosis on the cause and impact of certain PV module failures and allow for early detection of severe failures. This leads to the conclusion that field inspections and predictive maintenance are crucial for capturing less obvious but impactful failures, such as module degradation or mounting structure defects.

The standardized classification of failures also reveals interesting patterns in emerging system types such as floating PV, as shown in Figure 6, where some component failure distributions differ from ground-mounted systems due to the unique environmental stresses of water-based installations.

3.3.2 | Downtime of Failures

The analysis of O&M tickets shows that failure resolution times vary significantly depending on the component affected and event type. Statistical analysis of resolution times across component types reveals that all tickets show a median downtime value of 5.7 h, with a shorter duration in case only one inverter is affected and a longer duration for events concerning multiple inverters or the entire system. However, outlier cases with complicated fault diagnosis can extend to several hundred hours, particularly for intermittent issues that require multiple intervention attempts [48].

Gallmetzer et al. [85] proposed an automated decision support system (DSS) to optimize maintenance scheduling and reduce

downtime. The integration of automated failure detection with predictive analytics could shorten the average repair time. Figure 7 illustrates the median time required to close maintenance tickets based on different components and events.

Long downtimes are critical and should be avoided. A ticket should be opened and closed within a few days. Automated workflow and the help of field robotics can reduce these long downtimes. Particularly promising are autonomous inspection techniques using drones and ground robots equipped with thermal and optical sensors, which can reduce human intervention time while increasing inspection coverage and accuracy [86].

The resolution time depends not only on the nature of the failure but also on spare part availability and maintenance contract terms. Analysis of fixing times reveals wide variation in how these components are reported and addressed among O&M operators. Some operators primarily report fixing time in minutes while others report in hours or days, suggesting different interpretations of what constitutes repair time versus total issue resolution time.

Finally, the economic impact does not correlate linearly with downtime duration, as the specific component affected, and time of year prove more significant determinants of revenue loss. Analysis shows a weak correlation (approximately 0.2) between ticket duration and yield loss, indicating that short-duration failures of critical components can have greater economic impact than longer outages of less essential elements.

3.3.3 | Cost Impact of Failures

Most severe failures in PV systems, especially those concerning the inverter, result in revenue losses due to the unavailability of power generation, potentially leading to contractual penalties under Power Purchase Agreements (PPAs), and additional operational expenses.

Herz et al. [87], in the IEA PVPS Task 13 Report, present comprehensive methodologies for quantifying the economic impact of PV system failures, building upon the foundational cost priority number (CPN) methodology originally developed by Moser et al. [88] and subsequently refined by Hernandez et al. [89]. This approach provides a standardized framework to assess the financial weight of failures in EUR/kWp. The CPN formula is expressed as:

$$CPN = C_{down} + C_{fix} \text{ [euro/kWp]}$$

Where:

C_{down} : downtime costs due to energy loss

C_{fix} : fixing costs including detection, repair, transport, and labor expenses

An evaluation of 4,680 maintenance tickets with sufficient data revealed CPN values ranging from 0 to 16.19 EUR/kWp, with an average around 0.027 EUR/kWp per ticket. Though seemingly low, this value is normalized per unit capacity, meaning that

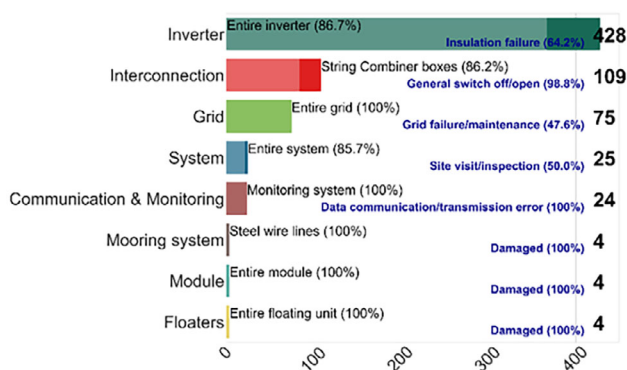


FIGURE 6 | Ticket statistics for floating PV. Analysis reveals that inverter-related issues remain the most frequently reported component failures, but with a distinct failure profile compared to ground-mounted systems. The predominant inverter failure mode is insulation failure, reflecting the challenges of water-based installations and increased moisture exposure. Interconnection failures represent the second most common component issue, with string combiner boxes being the primary concern within this category, highlighting the vulnerability of electrical connections in aquatic environments. Floating-specific components such as mooring systems and floaters show relatively low failure rates.

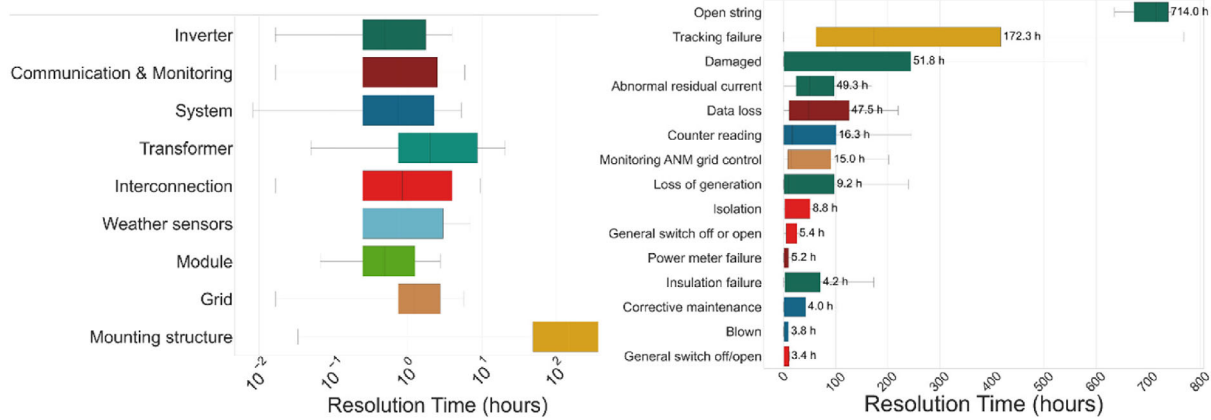


FIGURE 7 | Distribution of resolution times for PV system maintenance events. The boxplot on the left shows the distribution of resolution times in logarithmic scale across the main components of a PV system, highlighting typical downtime durations and variability between components. The boxplot on the right presents some selected events with a relatively high median resolution time (among those with more than 50 reported tickets). The median values are highlighted for each event.

even small per kWp values can represent substantial losses for multi-megawatt plants.

Case-specific assessments [48] shown in Table 2 highlight the importance of detailed failure documentation. For instance, inverter fan failures show a CPN of 0.0027 EUR/kWp for a fuse replacement and up to 0.0222 EUR/kWp when the fan itself required replacement. More complex inverter issues like inefficiency or DC protection faults reached values over 0.06 EUR/kWp.

These insights demonstrate how the CPN framework supports data-driven prioritization of O&M activities. By integrating this methodology into digital platforms and decision support systems, operators can make informed choices about spare parts management, preventive actions, and resource allocation on top of being

able to benchmark O&M over the whole portfolio where the O&M cost will be the sum of the CPNs over 1 year.

Beyond the CPN methodology, Herz et al. [82] present several complementary approaches for technical risk assessment in PV systems that provide valuable frameworks for a comprehensive assessment of the impact of failures. Reliability, availability, and maintainability (RAM) analysis provides insights into component-level reliability by modeling failure probability density functions, where different components follow specific distribution patterns. Inverters typically demonstrate lognormal distributions, while modules tend to follow exponential distributions. Bypass diodes and other electrical components often exhibit Weibull distributions in their failure patterns. This approach enables statistical prediction of component failures over time and supports proactive maintenance planning. In

TABLE 2 | CPN calculation of O&M tickets by Gallmetzer et al. [48].

Component	Subcomponent	Event	eventID	C_{down} , €/kWp	Solution	C_{fix} , €/kWp	CPN, €/kWp
Inverter	Fan	Failure	inv.48	0.0021	Reset inverter	0.0001	0.0022
					Replace fuse	0.0006	0.0027
					Replace inverter fan	0.0066	0.0087
Inverter	Fan	Failure	inv.48	0.0116	Reset inverter	0.0002	0.0118
					Replace fuse	0.0009	0.0125
					Replace inverter fan	0.0106	0.0222
Inverter	Entire inverter	Inverter failed to start due to DC protection	inv.21	0.0143	Automatic reset	0.0005	0.0148
					Replace DC breakers	0.0071	0.0214
Inverter	Entire inverter	Inverter inefficiency	inv.22	0.0079	Reset inverter	0.0001	0.0080
					Reset UPS	0.0001	0.0080
					Isolate faulty module	0.0006	0.0085
					Replace inverter fan	0.0059	0.0138
					Replace inverter	0.0582	0.0661

addition, the study presents methodological improvements to traditional Failure Mode and Effects Analysis (FMEA) by incorporating component-specific risk models and assigning probability distributions to different failure modes. This multi-method approach allows operators to triangulate risk assessments using different techniques, providing a more robust decision-making tool than a single method alone.

Technical risks from a reliability perspective, as introduced in the RAM analysis, are addressed in IEC TS 63265—“Reliability practices for the operation of photovoltaic power systems.” Its motivation is to provide a toolkit description of many methods of how different stakeholders can demonstrate the effectiveness of reliability increasing measures from technical and economic point of view [82].

3.3.4 | Safety and Security Issues due to Failures

Besides economic and operational impact, failures also cause environmental damage and pose health and safety risks to people. Common safety concerns include electrical hazards, fire risks, structural failure, and impacts to grid stability. Ara et al. [83] mention fault inverters and damaged connectors as potential cause for electrical shocks or short circuits, with severe consequences during maintenance activities. Junction box defects and inverter malfunctions have been linked to thermal events leading to fires, affecting both system components and surrounding infrastructure. Mounting system defects or extreme weather events can result in panel detachment, creating physical hazards particularly in high wind areas. Certain inverter failure modes can affect grid stability through unintended disconnection or power quality issues, leading to potential regulatory penalties.

Some failures create longer-term cascading risks, where initial minor defects progressively worsen into major safety hazards if not addressed immediately. For example, backsheet cracks can lead to moisture ingress, delamination and eventually electrical insulation failures.

Addressing these risks requires regular preventive inspections, compliance with safety standards, and proper training for maintenance personnel. Decision support systems can help handle safety procedures more efficiently, reducing resolution times and failure impacts.

3.4 | Preventive and Corrective O&M

3.4.1 | The Changing Paradigm of PV Maintenance

The European PV sector has reached an inflection point, where the focus is shifting from rapid deployment to ensuring the long-term reliability, sustainability, and financial viability of PV assets. As Europe targets the integration of hundreds of gigawatts of PV by 2035, preventive and corrective operations and maintenance (O&M) are emerging as a strategic priority. No longer viewed as a mere operational necessity, streamlined PV O&M is now central to asset valuation, risk mitigation, and sustainability [83]. The 2024 ETIP-PV Strategic Research and Innovation Agenda (SRIA) [2] identifies the enhancement of PV systems’ lifetime, reliability, and circularity as a core challenge, emphasizing that

operational excellence in PV maintenance and quality assurance will be just as pivotal as technological innovation in shaping the sector’s future. In this emerging landscape, PV maintenance is not anymore seen as just a “cost center” but a critical enabler of reliable, bankable, sustainable, and eventually future-proof PV deployment across Europe.

Traditional PV maintenance approaches, which often treat preventive and corrective actions as separate domains, are giving way to integrated systems that combine predictive analytics, advanced diagnostics, and circular economy principles, from component to PV system level. This shift reflects the maturing understanding that reliability cannot be achieved through sample testing or periodic inspections alone, but requires continuous top-down performance monitoring, coupled with sophisticated failure prediction models [83]. The ETIP PV experts have identified this integration as critical to achieving Europe’s 2035 PV deployment targets while maintaining investor confidence in PV assets.

Latest industry and real-field data reveal troubling trends that underscore the urgency of this transition. According to SolarPower Europe and H2020 TRUST-PV experts, up to 30% of the PV plants of, are underperforming, even when equipped with a mainstream PV monitoring system [83, 90]. Besides, the analysis of utility-scale PV plants installed between 2010 and 2015 shows that nearly two-thirds are experiencing degradation rates exceeding their original projections, with average annual performance losses of 0.8% compared with the expected 0.5% [91]. In the latter case, such discrepancy translates to significant financial impacts over a plant’s lifetime, potentially reducing net present value by 15%–20% for assets relying on merchant power sales. Such findings have forced a re-evaluation of PV maintenance and diagnostic strategies across the sector, with particular attention to climate-specific degradation patterns and the economic implications of different maintenance and diagnostic approaches [92, 93].

3.4.2 | Preventive Maintenance: From “Per-Schedule” to Data-Driven Approaches

Preventive maintenance (PM) of PV systems undergoes a significant transformation lately, evolving from a static, schedule-driven process to a dynamic, data-driven approach. Modern PM frameworks now incorporate advanced diagnostics, predictive modeling, and materials science to address the evolving challenges of maintaining PV systems. This shift is driven by a deeper understanding of how different components degrade based on factors such as technology, climate, and system design [65, 94–96]. For example, PV modules in Alpine and high latitude (Nordic) regions typically face different degradation patterns than those installed in the Mediterranean climate, with, for example, backsheet cracking and encapsulant discoloration progressing at different rates depending on factors like ultraviolet (UV) exposure, thermal cycling stressing, or hotspots—because of electrical mismatches—due to soiling or snow [4, 93].

In this context, PM strategies are becoming increasingly climate-specific, and PV O&M service providers consider implementing tailored maintenance protocols for PV plants installed in regions with distinct environmental stress profiles. For instance, in

Scandinavia, where snow loads and extreme temperatures are common, maintenance programs prioritize structural inspections and mechanical stress testing [93, 97, 98]. Conversely, in Southern Europe, plants focus on UV degradation monitoring and mitigating soiling effects [93, 99, 100]. Climate-specific PM strategies have shown potential for substantial improvements in PV performance and reliability, with operators reporting timely diagnosis of site-specific losses and likely reduction in unplanned downtime of up to 30%, according to certain demonstrations in the framework of the recent H2020 project SERENDI-PV [101].

Further, the digitalization of PV systems' operations [102], along with the smartification of PV inspections, are playing a crucial role in advancing the efficiency of PM. IR image-based inspections remain the main qualitative approach for PM [103–105], yet their limitations in accurately quantifying power losses and distinguishing certain failure modes (e.g., shading vs. soiling; multihotspots vs. potential induced degradation (PID)) have spurred the development of complementary diagnostic techniques. Indicatively, luminescence imaging can detect, e.g., moisture ingress in backsheets or cell microcracks long before visible signs or hotspots appear, while UV fluorescence imaging can identify early-stage encapsulant degradation and component-level mismatches that conventional methods (e.g., IR imagery or IV tracing) will typically miss to detect [106–108]. Leading PV O&M service providers are now integrating these methods into synchronized inspection protocols, combining their strengths for a more comprehensive PV state-of-health (SOH) analysis [83].

In addition to these advanced diagnostics, predictive analytics emerge as another potential gamechanger in PM for PV [109, 110]. Future O&M strategies will be required to incorporate weather data, component-level historic data and even supply chain information into sophisticated PV failure prediction models. Such approaches go beyond performance monitoring, by deploying data-driven maintenance actions based on cost–benefit analyses that consider factors like part availability and anticipated weather conditions during repair windows [111]. Besides, recent research innovations on edge computing could support—among others—the processing of real-time PV data at substation or inverter level, feeding into PV digital twin simulations that could forecast multiple degradation scenarios, enabling proactive rather than reactive maintenance [112].

According to Solar Bankability [113] and IEA PVPS Task 13 [87, 114] experts, preventive maintenance must be embedded early in the design phase of PV systems to minimize the impact of technical risks in PV projects' lifetime, while optimizing availability and, consequently, long-term PV energy yield. Selecting materials and system configurations that minimize maintenance needs (such as modular inverter architecture, bifacial modules with self-cleaning coatings, and optimized cable routing for easier access and thermal management) has become an essential part of design-for-reliability (DfR) principles. These principles, supported by lifecycle assessment tools, ensure that maintenance challenges are minimized from the outset, rather than being addressed as an afterthought.

The SRIA also advocates for efforts to standardize metrics for PV reliability assessment and prediction. European research projects and standardization bodies are working to define performance degradation thresholds, condition monitoring indicators, and intervention timing protocols. In alignment with the SRIA's focus on lifetime assurance strategies, such “harmonization” is critical for ensuring scalability across the European market and facilitating transparent benchmarking.

3.4.3 | Corrective Maintenance: From Recovery to Learning Loop and Circularity

Corrective maintenance (CM) remains indispensable for handling unexpected failures in PV systems, including grid disturbances, and large-scale (systemic) losses after extreme weather events. In recent years, the strategic role of CM has rapidly expanded from simply “detect/diagnose and (if necessary) repair” to also include “root-cause analysis and adaptation/learning,” particularly in PV design optimization and “repair/reuse” from a PV circularity perspective [115–117].

Aligned with this paradigm shift, SRIA calls for advanced corrective strategies that incorporate root cause analysis and closed-loop feedback into the design, O&M, and end-of-life (EoL) phases of a PV project. This is especially important for avoiding recurrent failures, updating PV reliability models dynamically and eventually employ DfR and prepare-for-reuse principles throughout PV projects' lifecycle [117]. Modern CM now employs AI-enhanced fault classification systems, cloud-based incident logging, and fleet-level performance benchmarking, enabling operators to identify systemic weaknesses—not just isolated issues [101, 118–122].

As often highlighted in recent studies and research/innovation projects, CM strategies must now consider resource and sustainability dimensions. For example, component replacement decisions are increasingly evaluated based on embedded carbon, recyclability, and critical raw material content. This perspective encourages repair over replacement and supports circular economy loops through component reuse, refurbishment, or resale [123–125].

Besides, as laid out in SRIA (Roadmap 2) [2], a key challenge in advancing (and transitioning towards) circularity in PV systems' operations, lies in the current limitations of CM practices, particularly in diagnostics, classification, and decision-making processes at the field level [115]. There is a pressing need for validated, cost-effective, and scalable tools that can accurately assess the state-of-health of PV modules and components after years of operation or exposure to extreme conditions. Today's CM often lacks standardized PV faults taxonomy and structured protocols for identifying which components are suitable for repair, reuse, or recycling, which hinders both operational efficiency and sustainable EoL strategies [115]. Moreover, the industry faces a gap in the deployment of automated, non-destructive diagnostic techniques and smart classification systems capable of supporting large-scale assessments directly in the field. Without consistent data on performance degradation and failure types, it becomes difficult to implement informed, reliable triage and decision-making procedures. This challenge is compounded by the limited integration of such diagnostic capabilities into PV

asset management systems, making it harder to support circular approaches like requalification, second-life use, or targeted repairs. Bridging this gap will be essential for reducing losses, improving the lifetime performance of PV plants, and enabling practical reuse pathways across the value chain [117].

Moreover, CM tasks are being tied to contractual and financial instruments, such as performance-based SLAs and O&M insurance. These tools depend on transparent CM data, failure resolution times, and yield recovery metrics, all of which are now key inputs into bankability models [87, 114]. Investors and insurers are demanding automated incident logs, performance recovery tracking, and predictive risk assessments, supported by third-party audits or platform-integrated tools.

Finally, the importance of workforce skills and training in executing high-quality CM is increasingly evident. As the document notes, expanding PV capacity in Europe will create bottlenecks unless there is a significant upskilling in digital diagnostics, failure analytics, and smart tooling operations [2].

3.4.4 | Maintenance as a Lever for Lifetime Extension and Investor Confidence

Maintenance strategies (Table 3) must no longer be viewed merely as operational necessities for PV assets, but rather essential pillar to the value proposition of PV as a resilient, investable, and sustainable infrastructure. By 2035, ETIP PV experts predict that preventive and corrective maintenance will shape the way PV systems are financed, insured, and certified across not only Europe, but worldwide. The connection of advanced PV O&M to bankability is explicit [83]: Robust maintenance frameworks reduce risk premiums, support lower cost of capital, and improve

project valuation. Lenders and developers increasingly rely on documented O&M histories and predictive reliability models to underwrite projects.

The SRIA stresses the integration of maintenance into broader digital ecosystems—from grid interaction protocols to ESG reporting frameworks. This includes the use of maintenance data for sustainability auditing, emissions tracking (from truck rolls to parts production), and digital product passports that accompany each major component across its lifecycle.

In conclusion, Europe's roadmap to a reliable and bankable PV sector by 2035 hinges on its ability to transform maintenance from a reactive, technical task into a strategic function that connects technology, finance, and sustainability [2].

3.5 | Perspectives of Reliable PV Systems

The reliability and lifetime of a PV plant depend mainly on the quality of the components. The economic impact is a function of the number of failures and the lead time to detect a failure, to respond after the detection and to ultimately resolve the issue as seen in Section 3.3.1 *Frequency of failure statistics*. The economic impact can be reduced by means of mitigation measures which can be preventive or corrective as seen Section 3.4.1. *The Changing Paradigm of PV Maintenance*. In new PV projects, the focus must be on the application of novel preventive mitigation measures. These can vastly reduce and minimize the probability of failure occurring in the field once the PV plant is in operation. For existing PV projects, advanced data driven mitigation measures need to be developed to go beyond the state-of-the-art concept of corrective maintenance as well as progressive repowering

TABLE 3 | Overview of maintenance actions and their impact on the PV systems.

Aspect	Preventive maintenance	Corrective maintenance	Predictive maintenance	Extraordinary Maintenance
Objective	Avoid failures before they occur	Restore functionality after failure	Anticipate failures using real-time data, analytics and system condition	Restore or secure system following major/unforeseen events
Key activities	Visual inspections, thermography, cleaning, firmware updates	Troubleshooting, component replacement, reconfiguration	Condition-based indicators, AI/ML based forecasts	Structural interventions, retrofitting, emergency response
Tools/ technologies	Checklists, maintenance protocols, visual/manual check	Remote monitoring, sensor diagnostics, failure mode analysis, incident logs	SCADA, digital twins, sensors, drones, machine learning	Engineering assessment, heavy equipment, redesign or rebuilding tools
Timing	Scheduled or condition-based	Unscheduled, event-triggered	Dynamic – based on live system data and predictive indicators	Unpredictable, driven by force majeure or large-scale disruption
Impact on system	Minimizes downtime and degradation	Resolves performance loss or safety risk	Minimizes unplanned downtime, increases system reliability	May cause major downtime or long-term operational interruption
Relation to SRIA objectives	Supports lifetime extension, circularity, and quality assurance	Enables data feedback, risk mitigation, and improved reliability	Advanced diagnostics, digitalization, failure prevention	Climate resilience, long-term system stability, risk mitigation

interventions to extend plant lifetime and increase the production capacity without requesting additional space. Planning of future PV plants must also consider the impact to the distribution or transmission grid and solutions must be introduced to enable seamless integration. All data coming from the various phases carry important information that can only be fully exploited by the community if the data can be stored and transferred along the value chain. The goal is to be able to “quantify” quality in a “value chain” approach by not being locked in a specific phase so that a PV project in the future can have access to lower Weighted Average cost of Capital (WACCs) by presenting bankable approaches, products and services.

PV projects in any market segment require a dedicated technical risk framework where the requirements may vary depending on the complexity of the project. In general terms, initial risks need to be identified and quantified, and all the stakeholders operating in various phases along the value chain need to be involved to vastly reduce and minimize the residual risks. This can be done by preventing the occurrence of failures and by reducing the impact of failures once they become evident. Technical risks which cannot be transferred to other stakeholders will ultimately stay in the hands of the PV project owner. A clear technical risk framework is important as it can “quantify” the quality of a PV project and thus demonstrate the advantages in terms of business model (more reliable generation for a longer lifetime) compared with other projects of lower quality. A project perceived of high quality by lenders (in terms of equity or debt) will have access to lower WACC (for example, a 4% interest on debt and 14% on equity with a 70/30 debt to equity ratio would give a 7% nominal WACC, if the interest on equity is 10%, the WACC would be reduced to 5.8%) which is the most important parameter affecting the LCOE, and ultimately the IRR (or other benchmarks) [60]. Quality in PV projects starts from the planning phase where a fundamental role is played by the accuracy and uncertainties related with the yield assessments. A yield assessment with reduced uncertainties (thanks to improved models and access to better site dependent data, e.g., irradiance) can lead to a much more favorable business model. Procurement is the next important step where extended testing beyond what is prescribe by the standards can increase the confidence of the right choice of PV components.

It is during these two steps that the remuneration of PV projects can be vastly improved by ensuring a reduction in failure rates and a more positive business case. After a successful implementation of these preventive mitigation measures, the PV project needs to focus on the transportation and installation phase where quality assurance needs to be included to make sure that all the components are in their best conditions for the operational phase. A reliable generation for a longer lifetime can then be ensured by innovative O&M practices which include data-driven measures coming from both field experience and monitoring. Finally, all the information collected along the whole value chain need to stream into digital platforms that can act as a decision support system for the best actions to follow in case of deviations.

Any future innovation carried out at each individual layer (component, system, grid connection) must become the consequence of a push-pull approach between stakeholders operating in clearly well-defined and separated phases of a PV project

which usually work with only their main objectives in mind and have little or no influence on the other stakeholders.

As an example, a PV module manufacturer has as a target cost per Watt and lifetime of the product, but they do not envision innovation which might have an economic benefit in terms of ease of installation or more effective O&M as this might have an impact on the CAPEX, similarly, for inverters. The same is valid for the information gathered during the project planning phase which is not transferred to the actors involved during the operational phase losing important insights coming from yield assessments (reason behind some choices in terms of design), procurement and quality assurance.

As previously mentioned, mitigation measures can be broadly divided into preventive and corrective measures. Preventive measures are applied before the risk occurs to prevent it from happening. The costs are mostly related to the CAPEX due to the earlier implementation during an earlier project phase (e.g., during PV plant planning and design). In this category, we have all the mitigation measures that have an impact on the overall uncertainty for the calculation of the energy yield. A reduction in uncertainty can lead to higher values of the energy yield at high exceedance probability, e.g., at P90.

In addition to the uncertainty related technical risks, this category of mitigation measures influences the number of failures happening during the operational phase. These measures have a great influence, for example, on the CPN value of the risks. For instance, in cases of failures related to low quality design, the number of failures can be drastically reduced by 90% [126]. The parameter number of failures is of great interest as it influences the losses due to downtime, the losses due to repair time, and the cost of substitution as seen in Section 3.3.1 *Frequency of failure statistics*.

For this reason, preventing the occurrence of failures can improve the attractiveness of PV projects even though initial investment might be higher. On the other hand, the added value of the PV plant after these measures must also be considered, especially in cases such as resale of the PV plant. The following mitigation measures typically belong in this group: component testing, design review and construction monitoring, and qualification of EPC.

Each action influences different groups of failures and different components. However, in some cases, the detected number of failures can be minimized due to the combination of mitigation measures by, e.g., applying design review and qualification of EPC, which will significantly reduce the risk of failures during the installation phase due to low-qualified personnel.

Mitigation corrective measures reduce higher losses and costs, if the risk has already occurred. The costs are mostly related to OPEX due to the later implementation during the operation and maintenance phase. Actions that influence the parameters such as time to detect, time to repair, and substitution time belong in this group of mitigation measures. Examples of these measures are: implementing advanced monitoring system for early detection and diagnosis of faults, advanced inspection (e.g., using infrared, electroluminescence, and photoluminescence cameras) to detect defects not usually visible with the naked eye, visual inspection

to establish any visible changes in PV plant components, and spare part management to minimize the costs of downtime and repair/substitutions of components). In particular cases, e.g., monitoring system, the mitigation measure cannot be assigned to a single category, and both characteristics in terms of impact and costs must be considered.

In the coming years, as the availability of measured data will exponentially increase, it will be important to build large databases with a potentially uniform method to increase the confidence level of the statistical analysis and thus reduce the perceived risks for PV investors. With the availability of these large databases, the necessary information (minimum requirement) can be filtered out to perform tailored analysis in a uniform way, i.e., same granularity, same data, and same formulas. For example, the CPN methodology and approach described in Section 3.1 attempt to provide such a benchmark.

Digitalization and the emerging new wave of generative AI are creating the framework to enable cost effective continuous condition monitoring by combining advanced diagnostic techniques with robotic solutions [127–129]. In the coming years, large language-based AI models (LLM) will reshape engineering software for renewable energy asset operations, driven by the urgency to enhance human–computer interaction. The tech giants’ rivalry underscores the rising significance of LLMs in the tech landscape. These models, adept at comprehending instructions and configuring settings seamlessly, promise significant time savings by expediting data queries and contextual data visualization. As the PV sector grows in complexity, these models are set to become indispensable tools, streamlining operations, and ensuring efficient asset management. The aim is to achieve an AI-based insights that through language models can be controlled by the user in dashboard/output/report creation. Asset managers will rely on language-based models/semantic queries that will gather data from various partner’s federated and interoperable digital platforms and provide various levels of feedback and actions depending on the user/stakeholder. This will allow some users to bypass graphical user interfaces giving them the power to gather information simply via vocal commands. The automation of reporting based on bespoke instructions will free technical operators from the burden of carrying out tasks that can be fully automated and dedicate more effort in improving the profitability of the PV assets.

4 | Bankable PV Projects

The bankability of a PV project is determined by its ability to attract investment through demonstrable performance, reliability, and risk mitigation across all phases of its lifecycle. This chapter provides an overview of the key performance indicators (KPIs), quality assurance measures, and risk profiles that influence the technical and financial viability of PV projects.

4.1 | Key Performance Indicators

Key performance indicators (KPIs) are essential tools for assessing the performance of solar PV systems. In this chapter, the most important KPIs of three relevant categories—**technical**,

economic, and **sustainability**—are being listed and briefly introduced. They reflect different evaluation goals throughout a PV system’s lifecycle. Technical KPIs support system design, operational benchmarking, and maintenance planning. Economic KPIs inform investment decision-making and project financing. Sustainability KPIs address the environmental and energy-related impacts of PV systems, supporting broader decarbonization and resource-efficiency goals.

Table 4 summarizes the most relevant KPIs identified in recent literature and industry standards, particularly those compiled by the IEA PVPS Task 13 [130]. Each KPI is listed with its primary function and its main application domain.

In line with SRIA, the correct definition, computation, and interpretation of KPIs are indispensable to gain insights into the lifetime, reliability, and sustainability of solar PV. Despite the existence of international standards such as IEC 61724, regional variations, methodological inconsistencies, and data quality challenges persist. High-resolution, reliable data, and transparent methodologies are essential to ensure that KPIs meaningfully reflect system performance, financial viability, and environmental compliance. As PV systems evolve with new technologies and deployment contexts, the role of comprehensive KPI frameworks will become increasingly central to risk assessment and investment decision-making.

4.2 | Quality Along the Value Chain

Every photovoltaic project can be different especially when it involves various market segments, products, etc. Stakeholders can vary from projects to projects, when they are involved and along which phases of the value chain, they are active. In general, there is no right or wrong, and similar projects can experience different workflows. However, for the sake of introducing cost-effective considerations and quality gates, it is important to map the workflow in a matrix with predefined stakeholders and value-chain steps. Within the IEA PVPS Task 13 [131], a framework has been developed which highlights the interconnected nature of decisions and their long-term impact on asset value, making it an essential tool for strategic asset management and performance optimization. The process of quality assurance is of fundamental importance to ensure that all elements of a project are of high quality for all involved stakeholders. In the project “Solar Bankability,” the Bankability of a project—strictly connected with quality—was described as “active quality management process,” where all stakeholders in the approval process of a PV project attempt to identify legal, technical, and economic risks throughout the entire project life cycle. These risks need to be quantitatively and qualitatively assessed, managed, and controlled. Once the risks are defined, as seen in Section 3, their impact can be vastly reduced by preventive mitigation measures, corrective mitigation measured, and transfer of risks to other stakeholders (e.g., insurance companies). The remaining risks will stay with the owner or operator of the asset. Mapping the workflow allows for an effective visualization of the process where “quality gates” can be introduced.

A “Quality gate” is a concept widely applied in the IT sector and refers to a milestone in a project that requires that predefined criteria can be met before the project can proceed to the next phase [132]. It is important that quality gates are included after a clear

TABLE 4 | Summary of key performance indicators for PV systems.

KPI	Definition	Application
Technical KPIs		
Pxx Energy Yield (P50, P90, P99)	Probabilistic estimate of energy production based on long-term weather data	Risk assessment, financial modeling (e.g., debt structuring)
Performance ratio (PR)	Ratio of actual energy output to theoretical output under standard test conditions (STC)	Operational benchmarking, performance guarantee tracking – widely used KPI in Europe and other markets
Energy performance index (EPI)	Ratio of actual to expected energy yield from performance model	System health monitoring, reduced weather dependency
Availability	Operational uptime relative to potential production time	O&M contract compliance, reliability tracking
Soiling ratio (SR)	Energy loss due to dust/dirt on modules	Maintenance scheduling, site-specific cleaning strategy
Degradation rate (Rd)	Long-term, irreversible loss in performance	Long-term yield forecasting, technology evaluation
Performance loss rate (PLR)	Combined reversible and irreversible (Rd) performance losses of PV system	Lifetime performance modeling, system health tracking
Capacity test	Plant performance evaluation under standardized environmental conditions (can differ from STC)	Commissioning validation, EPC handover
Capacity utilization factor (CUF)	Actual energy output relative to theoretical max (based on AC rating), also known as plant load factor (PLF)	Cross-plant performance comparison
Maintenance response time	Time from fault detection to corrective action	O&M efficiency, asset management performance
Economic KPIs		
Levelized cost of electricity (LCOE)	Cost per unit energy over system lifetime	Cost competitiveness, investment assessment
Net present value (NPV)	Present value of net cash flows over project lifetime	Financial viability screening
Internal rate of return (IRR)	Discount rate where NPV equals zero	Investment attractiveness indicator
Sustainability KPIs		
Global warming potential (GWP)	Lifecycle greenhouse gas emissions per produced kWh	Environmental impact assessment, technology comparison
Energy payback time (EPBT)	Time to recover energy invested in system creation	Resource efficiency evaluation
Energy return on investment (EROI)	Ratio of lifetime energy output to energy input	Sustainability performance indicator

cost–benefit analysis and the expectations is that more quality gates are introduced in the initial phase to prevent the manifestation of risks, rather than in later stages where the correction of failures and low quality can become very expensive and not feasible.

The PV market is characterized by rapid technological advancements, abrupt regulatory changes, and fluctuating manufacturer leadership. Section 2.1.5 *Changes at the manufacturing level* discussed the specific challenges related to the introduction of TOPCon technology to the market.

Several global political initiatives have been launched post-COVID and the energy crisis to further incentivize the

deployment of solar energy and kick-off the reshoring of PV manufacturing. These initiatives include the EU Solar Strategy [133], the Net-Zero Industry Act (NZIA) [134], and REPowerEU [135] in Europe, as well as the *Approved List of Models and Manufacturers (ALMM)* in India [136] and the *Inflation Reduction Act (IRA)* in the USA [137].

This dynamic and policy-driven market evolution has resulted in most recent changes in the landscape of leading PV module suppliers. Some existing players extend their operations [138], while others steer their business elsewhere [139, 140], and new players plan to enter the market in the near future [141]. This is not new in the PV industry: Over the last decade, there has been

significant shifts in the geography and actors of the top global PV supply, with the list of Tier 1 vendors changing almost annually [142]. This volatility of manufacturer leadership, in combination with policies dedicated to manufacturing reshoring, drives the creation of a more diversified supply chain, with new manufacturing ecosystems growing across different regions of the world, and underscores the importance of strict due diligence during selection of PV modules.

Given the multidimensional challenges of PV manufacturing mentioned above, ensuring that product quality requires a holistic and structured approach that spans across the Procurement & Logistics and Construction & Commissioning phases, as discussed in Sections 4.3.3 *Procurement & Logistics* and 4.3.4 *Construction & Commissioning* and summarized in Table 5. By adopting a proactive and systemic framework, stakeholders can mitigate risks, enhance asset performance, increase investor confidence, and contribute to the sustainable growth of the global solar industry.

4.2.1 | Due Diligence

At the beginning of the procurement phase, a comprehensive due diligence process—targeting the manufacturer, manufacturing site, and the manufactured product—is an often underestimated but critical step in quality assurance. Early implementation of a structured due diligence strategy enables better supplier selection and risk mitigation. Buyers should assess corporate sustainability, financial health, and reputation of the manufacturer using third-party industry-recognized sources [143, 144]. The manufacturing site also needs to be assessed, by on-site audit of the quality management system and the manufacturing process, in line with the ISO9001:2015. The product due diligence should confirm that the module's design, technology, and sub-components align with the project's technical requirements.

4.2.2 | Technical & Quality Requirements

Once the supplier is selected, the procurement contract (or its annexes) should explicitly outline all technical and quality-related requirements necessary for manufacturing and delivery in alignment with both project-specific and industry-wide standards. To ensure safe operation and long-term performance, the contract should require compliance with international standards

such as IEC 61215 and IEC 61730 and local regulations, as well as advanced reliability testing programs certifications [145, 146]. Contracts should define pre-, in-, and post-manufacturing quality measures that will take place during the execution of the project, such as BOM verification, factory inspections, and laboratory and on-site testing. It is good practice to define at this stage the pass/fail criteria for acceptance or rejection of modules, the sampling quantity and the Acceptable Quality Limit in line with the ISO 2859-1, widely accepted industry standards [43, 147], and best practices [148].

4.2.3 | In-Factory Quality Control

Once all requirements and conditions are clearly stated in the purchasing contract, the quality of the product needs to be monitored to ensure that manufacturing aligns with both contractual and industry expectations. Shortly before the start of the manufacturing, pre-production checks take place to ensure readiness through equipment calibration and inventory validation. Similarly, several technology-dependent tests can be performed at independent, ISO17025-certified laboratory to verify product conformity and BOM qualification. Continuous monitoring of the production detects nonconformities at different process steps (see Figure 8) early and allows for immediate corrective actions, limits defect propagation, and enables rework of affected modules. Data suggest higher defect rates during night shifts due to reduced oversight [150], justifying round-the-clock presence during critical production phases.

Performed on the finished product at the end of the production, pre-shipment testing validates product conformity and uncovers risks that may not have been captured during earlier quality gates. In most factories, all modules are tested directly by the manufacturer for performance and safety, measuring Maximum Power Output and Insulation according to IEC 61215-2:2021 MQT02 and MQT03 and Electroluminescence (EL) according to IEC 60904-13:2018. Independent third-party retesting introduces an additional layer of quality by mitigating several manufacturing, performance, design, and technology risks. For instance, gel content test according to the IEC 62788-1 and peel-off test according to IEC 61730-2 verifies an appropriate outcome of the module lamination. Maximum Power Determination on the Rear Side of bifacial modules according to the IEC TS 60904-1-2:2024 ensure the consistency

TABLE 5 | Steps of quality assurance/quality control for PV modules along the value chain.

QA/QC step	Description	Example of quality actions
Due diligence	Early and thorough assessment of manufacturers, production sites, and product design to ensure quality and reduce risk	Site audit, corporate financial review, environmental social governance audit, technology compliance
Technical and quality requirements	Clearly defined technical standards and quality expectations in contracts are vital for project alignment	Compliance with standards, BOM verification, acceptance quality criteria (AQL)
In-factory qualitycontrol	Production monitoring and pre-shipment testing ensure product conformity and detect defects early	Performance, safety and performance and reliability lab tests
Construction and commissioning QC	Post-shipment inspections verify transport integrity and confirm modules meet specifications before installation	Performance tests, infra-red (IR) drone and electroluminescence tests

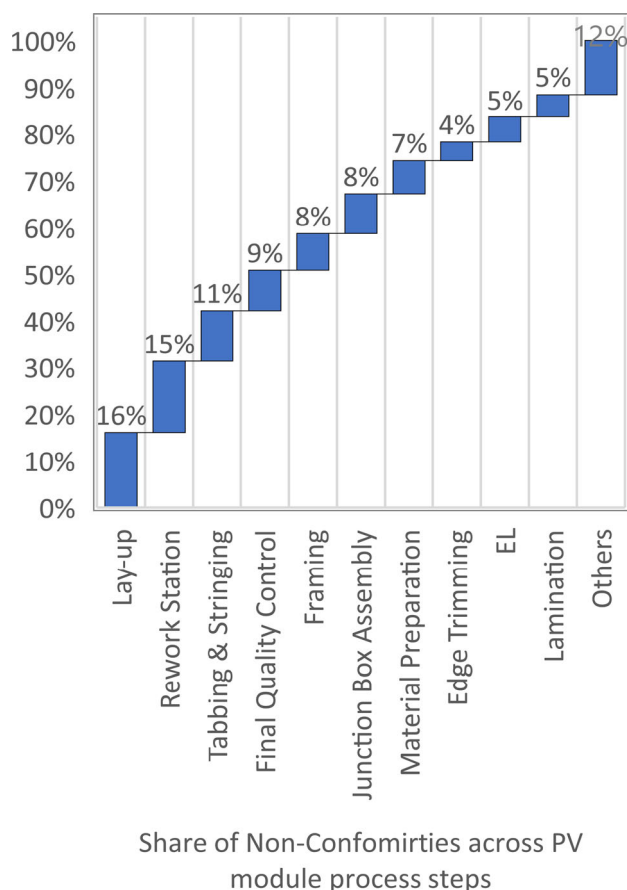


FIGURE 8 | Process steps reporting the highest number of non-conformities detected during monitoring of PV module production. Data averaged from STS and Kiwa's sources. STS data are extracted from all projects inspected in 2024. Kiwa's data are elaborated from publicly available information [149].

of in-line testing and assesses that module outputs match product specifications. Additional testing allows for verifying that module design complies with project requirements (e.g., static and mechanical load tests allows to evaluate compatibility with racking structure and climate conditions) and for estimating technology-specific long-term degradation: For instance, PERC technology should undergo light induced degradation (LID) test and ultra-violet induced degradation (UVID) tests could be beneficial to show early degradation of PERC [151] and TOPCon, respectively [152, 153].

4.2.4 | Construction and Commissioning Equipment Quality Control

Finally, quality control can also be continued during the construction and commissioning phase, with post-shipment testing such as EL imaging and Visual Inspection according to IEC 61215-2:2021 MQT01 ensures that modules arrive undamaged and meet delivery specifications.

4.3 | Risk Profiles of PV Projects

Photovoltaic power plants are complex systems composed of numerous interconnected components and processes, each of

which can introduce technical and operational risks. Unlike conventional power generation systems, the upfront capital expenditure for PV projects typically accounts for a significant portion—often up to 80%—of the total lifecycle cost. This cost structure makes the long-term performance of PV systems highly sensitive to early-stage decisions regarding design, component selection, installation quality, and maintenance strategies. Despite the apparent standardization of PV components like modules and inverters, project-specific variations in engineering, procurement, construction, and operational practices contribute to a broad range of outcomes in terms of reliability and energy yield. These standards often lag the rapid rate of technology developments in the solar PV sector and are a minimal baseline. Common sources of underperformance include component faults, poor installation practices, inadequate system monitoring, and environmental stressors such as extreme weather or soiling. These factors not only affect the technical performance of a plant but can also lead to significant financial losses, particularly when compounded over a 20- to 30-year operating lifetime.

To mitigate these risks, the industry is expected to increasingly rely on structured quality assurance frameworks and technical assessment methodologies. Conformity assessment systems such as IECRE [154, 155] provide standardized procedures for verifying compliance with international norms, but they lack widespread market adoption and may be considered limited due to their binary (pass/fail) nature. More advanced quality rating systems are required to provide a more comprehensive and nuanced evaluation of PV project risks, by assessing not only product quality but also process execution and site-specific factors. Advanced methodologies have already been developed [156] which integrate components (such as modules, inverters, and raw materials) and project-specific processes (such as engineering, procurement, construction, testing, commissioning, and operations and maintenance) into an overall risk profile, that results in project risk ratings from AAA (highest) to D (lowest) in a replicable and transparent procedure. As the solar sector continues to mature and attract long-term capital investment, transparent and consistent risk assessment mechanisms will play an increasingly critical role in ensuring project bankability, sustainability, and alignment with broader policy goals such as the energy transition and climate resilience.

Advanced quality rating systems that incorporate comprehensive and nuanced evaluation of PV project risk should account for technical, legal, financial, climate, political, and operational challenges throughout the different phases of an assets development to account for the different stakeholders. These stakeholders are typically lenders, developers, insurers, and investors.

4.3.1 | Development and Financing

Developing a utility and/or C&I solar farm requires executing preliminary assessments, which heavily impact a projects feasibility and bankability.

Among others during this phase, the weather file or solar resource plays a significant role in the estimation of risk in a project's bankability [157]. The 8760-h data and interannual variation can vary greatly and impact business cases. Measurement uncertainty, comparison with satellite data, transposition model,

Source of Uncertainty	Typical Range	Notes
Long-Term Annual Solar Resource Mean (GHI)	3.0-5.0%	This estimation from the satellite data provider is presented as typical and may vary from location to location.
Performance Model (including transposition)	4.0-7.0%	Uncertainty associated with estimation of model input parameters and accuracy of model in predicting energy generation through modeling steps
Inter-Annual Variability	2.8 - 5%	
Combined Uncertainty of Year 0 Yield	5.7-9.9%	Addition in quadrature: Square root of the sum of squares
Annual Performance Degradation	0.25 - 0.5%/yr	
Combined Uncertainty of Year 10 Yield	6.3-11.1%	Assuming a cumulative effect of 10 times the annual performance degradation uncertainty

FIGURE 9 | Listed sources of uncertainty for example project. Solar Bankability 2017 [159].

considerations for shading, and temperatures all play role in the forecasting of yield [158].

As seen in Figure 9, the square root of the sum of the squares of uncertainties can be used to determine the combined uncertainty, assuming component uncertainties are independent.

4.3.2 | Design and Engineering

During the designing of a PV system factors like forecasting energy, design flaws, equipment resilience, and quality along with costs at the site impacts project lifetimes and yield, especially its resilience to weather events. The frequency of extreme weather events and the severity will increase in the coming years [160]. These include the advent of higher wind loads and higher risk of flooding or hail. Standards that incorporate system design, commissioning, and operation like that of IEC 62738, IEC 62548, IEC 62446, IEC 61829, and IEC 61724 are minimum requirements and do not yet include the wide breath of requirements to advocate for resilience in different weather and climates. Baseline but critical gaps in the approach to corrosion, wind load, and grid connections are yet to be integrated or made into standards [161].

There are several loss factors in the process of estimating energy production, each having their own associated uncertainties. PVSyst which is typically used as a bankable system allows for the use of either Hay & Davies or Perez model to transpose DHI values to diffuse in plane of array. The empirically derived coefficients to model contributions of the non-isotropic components of diffuse light is generally deemed more accurate at estimating diffuse light incident on the GPOA.

Snow, separate from soiling losses, can have a greater impact on solar resource. Soiling ratio can have indirect effects on temperature and lead to additional energy losses [162]. Though precipitation can significantly reduce soiling ratios, the interaction can result in non-uniform, caked soiled build up [163]. Along with shading, either due to inter-row shading or horizon shading have a large measurement uncertainty as as-built conditions vary from those that are anticipated or modeled. Examples hereof include the (re)-growth of trees at the east of west side of the site.

A common approach is to use PVSyst is used as a physics-based model to represent a single diode equivalent electrical circuit model to convert light energy incident on the module to DC current and voltage, forecasting energy yield. Various coefficients and response curves are simulated to generate a prediction on future kWh production. These can be sources of uncertainty as shown in Table 6. An example hereof are module mismatch losses that are not accredited to varying temperature, irradiance, or soiling, but because of variations in the electrical parameters of different modules in a string. Given Fraunhofer ISE report [164] on module power output distortion being on the rise coupled with further power loss in bifacial systems due to non-uniform irradiance for bifacial modules [165], these losses can be significant. PAN files, which are digital datasheets used by PVSyst, have shown variation in and can exhibit different yields depending on which is selected [166].

The percentage decrease in output of DC electrical energy per degree Celsius above STC (1000 W/m² and 25°C) is also a source of uncertainty. These are typically based on a heat-balance model that is a function of air temperature, radiative, and wind heat losses to the environment. The uncertainty can range from $\pm 0.1\%/K$ for voltage and $\pm 0.02\%/K$ for current [167].

Inverters models captured as OND files in PVSyst attempt to capture inverter behavior under different conditions. Derating, the result of an inverters reduced cooling ability at lower air densities and higher temperatures which lead to a deduction in waste heat, and in turn power loss has now been modeled by PVSyst. It derates the AC capacity at temperatures above 50°C. Alongside as mentioned in Section 2.2. Inverters and BOS, clipping and curtailment has a negative impact on the lifetime and performance of inverters.

Availability is typically considered a constant loss of typically 0.99. Availability is a random process and can vary per on a grid, inverter, and system level. IEC 63019 attempts to standardizing energy-based availability. O&M contracts exclude some downtime events, wherein in the technical availability may at times be lower than reported [61]. This coupled with the same approach for curtailment impacts both energy yield, but also project lifetimes. The uncertainty of both can be modeled with

TABLE 6 | PVsyst modeling measurement uncertainty as presented by Reich et al. at the Photovoltaic Specialist Conference in 2015 shows the sources of uncertainty in the breakdown of the performance ratio losses and yield forecasting. Solar Bankability 2017 [103].

Sources of uncertainty		Uncertainty range % 1-sigma	
		Individual	Combined
A: Irradiation	Satellite GHI	3–5	4–6
	Direct/diffuse ratio, GPOA transposition	2–4	
B: Shading	Horizon	0–0.5	1–4
	Inter-row	1–4	
	External	0–3	n.a.
C: Soiling		1–4	n.a.
D: Deviation from STC	Reflection	<1	<2
	Spectral losses		≈1
	Irradiance intensity		1–2
	Temperature		1–2
E: Actual PV capacity and DC loss	Module power and mismatch	2–5	<5
	Cabling	0.5	
F: Inverter losses	Model related	<1.5	<2
	Power limitation	<0.5	
G: AC losses	Cabling	0.5	<1
	Transformers	0.5	
Combined total initial uncertainty		Typically 5%–11%	

probability distribution rolled into the P90, P75, or P50 models like that of Petr-net based model that allows stakeholders to gain insights at even a component level [168].

Failure mode effect analysis (FMEA) of PV systems provides a framework in which to determine the reliability and performance of a solar PV system—moreover the maintainability of system [169]. Mapping the different failures of components, not alone of PV modules, but also inverters, transformers, BOS in different applications and climates based. A further example here of is the occurrence of acid rain or naturally occurring salts a location on the degradation of polymers in DC cables or connectors [170]. Executing this based on literature review, field studies, and lab tests helps generate a risk probability number based on the severity, occurrence, and ease of detection of a that component to fail [171].

4.3.3 | Procurement and Logistics

During this phase supply chains, prices, quality, specifications, warranty compliance, and local content requirements play a role. As noted in Section 4.2 Quality along the value chain, various best practices can be implemented to mitigate known risks associated with challenges that can reduce PV module durability and reliability. In addition, the VDE90038 SMQS adds additional best practices to mitigate known risks with PV module procurement. This includes, but is not limited to gel content testing, peel tests, dynamic and/or static mechanical load tests, PID, and UVID testing [43]. Site considerations like climate, weather events, and wind and/or snow load impact on component degradation and failure rates are yet to be integrated but play an integral role

as failure rates and degradation are site specific and must be evaluated [42].

The implementation of these risk mitigation measures can be evaluated on the CPN as mentioned in Section 3.3.3 *Cost impact of failures*. Risk assessment and mitigation strategies are dependent on project size, application and component. The 2021 Solar Bankability report on *Mitigating Technical Risks in PV Investment through Quality Infrastructure* proposes different preventative and corrective measures. Among many, component testing based on a cost risk matrix.

In context of the Corporate Sustainability Due Diligence Directive (CSDDD) requires business to address negative impacts across their entire value chain and execute due diligence that is beyond desktop reviews. In light hereof, traceability requirements like that of the Solar Stewardship Initiative play role to foster responsible production, sourcing and stewardship of materials.

4.3.4 | Construction and Commissioning

Typically, developers opt for FIDIC silver book turnkey EPC contract with a 1- or 2-year warranty period. During this phase, the construction project starts and is typically broken down into different milestones. Those milestones as noted in the Solar Power EPC Best Practices guidelines include site preparation, pre-commissioning, mechanical completion, cold commissioning/practical commissioning, and hot commissioning/commercial operation. The end of construction works and obligations by the EPC is the conditional acceptance by the asset owner in form of the Provisional Acceptance Certificate (PAC). Finally, there is

the final acceptance certificate upon addressing the minor issues addressed in PAC and attaining the guaranteed performance ratio and availability during the given warranty period.

The Solar Bankability Technical Bankability Guidelines [159], recommendations to enhance technical quality of existing and new PV investments provides a checklist of contractual requirements in EPC contracts to mitigate known risks. These are in addition to IEC minimal requirements like that of IV curve, drone, Riso testing as according to IEC 62 446, but also definitions of availability and performance ratios as stated in IEC 61724-3:2016 and IEC 61724-1:2021 respectively. As argued, in Section 4.3.2 Design and Engineering, the integration of IEC 63019 helps better define availability. Interpretation and visual verification of known risks can be found in the IEA PVPS report from 2014 Review of Failures of Photovoltaic Modules [172]. The Solar Power Europe EPC best practices add an additional layer of best practices to mitigate known risks.

DC level connections between different components, known as strings by use of connectors can have an impact on the failure rate of inverters as noted in 3.1. Connectors contact degradation or improper installation in combiner boxes due to torquing or design can lead to arc fault events. There is a big human factor that comes into play when it comes to wire management hereof and the failure rate attributed to it during construction [170].

With the advent of Environmental Social Governance and EU Corporate Social Reporting Directive, reporting life cycle analysis of components but also systems come into play. EPCs with ISO14001 certification help provide a framework to report usage and waste management to monitor environmental performance. ISO1407x series, ISO14044 and ISO14040, help parties determine a framework in which to execute life cycle assessments of components but also systems. PV modules LCA or carbon footprint can be certified according to EPEAT, EPD, and ECS and vary in approach and requirement. The IEA PVPS Task 12 reports objectives focus on detailing energy, material and emission flows across the PV life cycle.

4.3.5 | Decommissioning and End of Life

The European waste framework directive provides a waste hierarchy in which the priority of handling goes from prevention, re-use, recycling, recovery and lastly disposal. The current WEEE mandates recycling. R&D efforts are focused on increasing recovery rates of PV modules. PV modules with proper QAQC measures, correct installation, and diligence maintenance may output more than 80% of their power at end of life. The EU Corporate Sustainability Reporting Directive alongside the advent of Environmental Social Governance requires asset holders to set goals in reducing waste and promoting re-use and repair of PV modules. Concerning recycling of PV systems, a study by the US Department of Energy from 2022 indicated that the estimated amount of PV materials that will enter the recycling stream in 2050 will be around 2% of the amount of steel, 25% of glass, and 6% of Al that was recycled in 2018 [117]. Hence, in terms of sheer volume, this can be well handled. When we look to the precious materials that are used in the PV cells such as copper, silver and silicon, these recycled PV materials can represent around two-thirds of the total monetary value of the materials making up the silicon PV cell.

There are currently no standardized norms for the re-use of PV modules [173]. Reuse of PV systems improves circularity, though currently not feasible the carbon footprint of PV systems is greatly reduced by reusing its components. The feasibility challenges lays in the business case of second-hand PV modules and high testing costs to de-risk and ensure technical viability.

4.3.6 | Perspectives

The long-term viability and bankability of photovoltaic power plants are intrinsically linked to comprehensive risk assessment and mitigation strategies that span the entire asset lifecycle, as discussed in the previous sections summarized in Table 7. Given the capital-intensive nature of PV projects—where up to 80% of costs are incurred upfront—technical and operational decisions taken during the early development stages, including site selection, component specification, system design, and

TABLE 7 | Risks and management strategies across the project lifecycle.

Project phase	Key risks	Mitigation strategies
Development and financing	Solar resource data, performance model and inter-annual variability uncertainty leading to inaccurate yield forecasting	Long-term ground measurement campaigns, combination of satellite and on-site data
Design and engineering	Weather resilience gaps, Uncertainty in models and component parameter files (PAN, OND), system availability variation	Inclusion of resource variability, soiling dynamics, extreme weather resilience, and uncertainty in modeling parameters, use of high-fidelity input data and stochastic modeling approaches
Procurement and logistics	Durability, reliability and traceability of components linked to value chain and project site considerations	Multi-criteria quality rating systems, standardized performance testing, adoption of traceability frameworks, ESG-aligned supply chain standards
Construction and commissioning	Installation and wiring errors, Inadequate testing and quality verification	Best industry practices, FMEA, lifecycle impact assessments
Decommissioning and end of life	Absence of standardized norms for reuse standards, low economic viability of second-hand modules	Planning for recycling and reuse in early project stages, Following WEEE directive

installation quality, exert a disproportionate influence on long-term energy yield, system reliability, and return on investment. Despite increasing standardization across PV components and practices, significant variability persists due to site-specific conditions, inconsistent project execution practices, and rapid technological innovation that frequently outpaces existing standards and regulatory frameworks.

As a result, an evolution in quality assurance frameworks and technical due diligence methodologies is required. Traditional conformity assessments, while foundational, are increasingly insufficient to capture the full spectrum of risks associated with modern PV deployments. A transition toward advanced probabilistic risk models and multicriteria quality rating systems is necessary to evaluate both component-level reliability and project-level execution in a nuanced, data-driven manner.

Furthermore, yield forecasting and system modeling must integrate a broader range of environmental and operational variables, including resource variability, soiling dynamics, resilience to extreme weather events, and uncertainty in modeling parameters. Tools such as PVsyst, when combined with high-fidelity input data, rigorous treatment of uncertainties, and stochastic modeling approaches (e.g., P50/P75/P90 scenarios), can provide more accurate and robust estimates of energy production and financial performance.

Procurement protocols and construction practices also require strengthening through the adoption of lifecycle impact assessments, traceability frameworks, and ESG-aligned supply chain standards. The implementation of robust quality infrastructure measures, including standardized performance testing, failure mode and effects analysis (FMEA), and lifecycle emissions tracking, will be vital for aligning project development with emerging regulatory requirements such as the EU Corporate Sustainability Reporting Directive (CSRD) and the Corporate Sustainability Due Diligence Directive (CSDDD).

Finally, the end-of-life (EoL) phase must be integrated proactively into project planning. While current regulatory frameworks such as the EU WEEE Directive mandate recycling, significant challenges remain with respect to module reuse, including the lack of standardized criteria and the limited economic viability of second-life PV markets. Enhanced R&D efforts and quality-controlled reverse logistics are essential to close the loop and improve circularity in the PV sector.

In summary, achieving true technical bankability requires a shift toward integrated, risk-informed, and standards-aligned approaches covering every phase from development to decommissioning. Projects that embed these practices will be better positioned to deliver long-term performance, strengthened investor confidence, and alignment with global energy transition and climate resilience objectives.

5 | Conclusions/Outlook

Advancing the bankability, sustainability, and resilience of PV systems requires an interdisciplinary and forward-looking

approach that embeds technical rigor, process transparency, and environmental accountability across the entire asset lifecycle. As PV deployment continues to accelerate globally, aligning quality assurance practices with these principles will be essential to securing the sector's contribution to long-term climate and energy objectives.

Despite increasing standardization of PV components and practices, substantial variability persists due to site-specific conditions, differences in project execution, and rapid technological innovation that frequently outpaces existing standards. Conventional conformity assessments are becoming insufficient to capture the full spectrum of risks associated with modern PV deployments. A transition toward advanced probabilistic risk models and multicriteria quality rating frameworks is required to evaluate both component-level reliability and project-level execution in a nuanced, data-driven manner. In parallel, yield forecasting and system modeling must account for a wider range of environmental and operational factors, including resource variability, soiling dynamics, resilience to extreme weather events, and uncertainty in modeling parameters.

Procurement protocols and construction practices must also be strengthened through the implementation of robust traceability schemes, ESG-aligned supply chain requirements, and lifecycle impact assessments. Finally, end-of-life (EoL) management needs to be integrated proactively into project planning. Although regulatory instruments such as the EU WEEE Directive mandate recycling, the absence of harmonized reuse criteria and the limited economic viability of secondary module markets remain significant challenges that must be addressed to enable a truly circular PV sector.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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Data associated with this article cannot be disclosed due to legal reasons.

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