Failure Rate of Photovoltaic Modules and Their Collection Numbers for Recycling

TNO 2025 R12777

TNO Public ⟩
19 December 2025

Energy & Materials Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

– 19 December 2025

Failure Rate of Photovoltaic Modules and Their Collection Numbers for Recycling

TNO 2025

Author(s)	E. Busra Kucuk Reviewers: Remi Aninat, Mirjam J. Theelen, Jan M. Kroon, Martin Späth, Kahya Engler
Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	41 (excl. front and back cover)
Number of appendices	0

Contents

Executive Summary

Global photovoltaic (PV) deployment has accelerated rapidly in the past decade, with cumulative installed capacity surpassing 2 TW in 2024 and annual additions exceeding 600 GW, which is significantly outperforming earlier market projections. As PV deployment accelerates, accurate estimation of end-of-life (EoL) PV module waste becomes increasingly critical for circular economy strategies, recycling infrastructure planning, and the management of valuable material streams. The International Renewable Energy Agency (IRENA) projected in its 2016 report that Europe would accumulate up to 3,000,000 tonnes of EoL PV module waste by 2030, depending on the assumed failure scenario (early-loss or regular-loss). Early-loss failure refers to modules that fail prematurely due to defects, damage, or unforeseen technical faults, while regular-loss failure of modules occurs after their expected 25–30-year lifespan under normal operating conditions. However, actual waste data has been much lower, with approximately 50,000 tonnes in 2022. This discrepancy underscores the need for updated methodologies aligned with current trends. This study, commissioned by Stichting Open and conducted by TNO, investigates the root causes of this divergence by reviewing recent literature on PV module failure rates, evaluating the applicability of IRENA 2016 waste estimation methodology, and analysing the impact of technological advancement, market dynamics, and region-specific factors of waste streams.

Technological advancements in PV module design have reduced certain failure modes, such as cell cracking and light-induced degradation (LID), while increasing others, like glass breakage and UV-induced degradation. Moreover, emerging evidence shows that many PV modules outperform their expected lifespans, with minor failures often not leading to immediate decommissioning. Additionally, PV waste projections should consider non-technical factors such as repowering and revamping strategies, second-hand markets, regulatory frameworks, installation practices, and end-user behaviour. These elements significantly impact EoL volumes and should be integrated into any waste stream model. Waste projections should integrate both technical factors (degradation rates, failure modes) and non-technical drivers (market, regions and user behaviour). The study applied a hypothesis-based waste modelling approach for the Netherlands, incorporating both early-loss and regular-loss forecasting scenarios and non-technical drivers to provide projections for future waste streams. We conclude that a new data-driven, region-specific methodology, which takes into account the above criteria, is essential for more realistic PV waste stream forecasting.

1 Introduction

1.1 Overview of PV technology

Over the past five years, the global PV market has experienced rapid growth with cumulative capacity surpassing 2 TW in 2024 and annual installations reaching more than 600 GW. Increasing global demand for clean energy, falling module prices and rising PV performance along with advancements in materials, manufacturing processes, and digitalization were driving factors of this rapid growth of PV module deployment globally. As PV module deployment accelerates, the photovoltaic industry is likewise experiencing a significant technological transformation. Until around 2016, the market was dominated by a single solar cell technology: Aluminium Back Surface Field (Al-BSF) cells. However, as efficiency demands grew, Passivated Emitter and Rear Cell (PERC) technology emerged as a superior alternative. By 2019, PERC had become the mainstream choice, capturing over 65% of the global market share due to its improved performance and compatibility with existing production lines. In 2023, PERC started losing its leading position to new high-efficiency technologies like Tunnel Oxide Passivated Contact (TOPCon), Heterojunction (HJT), and back-contact solar cells (see Figure 1). While there were only a few dominant technologies in the market previously, now the market hosts a wide range of solar cell technologies with different module design and material options.

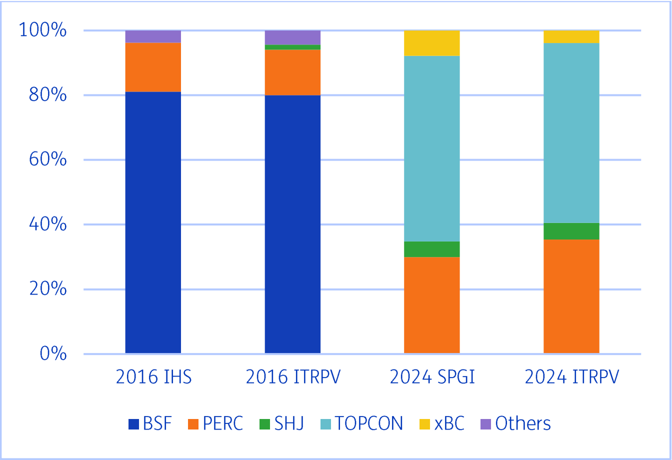


Figure 1. Market share of different cell technologies, [1-2]

As global deployment accelerates, the implications for end-of-life management and waste estimation become increasingly significant. In 2016, The International Renewable Energy Agency (IRENA2016) published a report regarding estimation of PV waste by using historical failure modes and degradation rates of PV modules [3]. In 2022, PV waste estimates were reviewed once more to compare with actual outcomes [4]. The discrepancy between projected PV waste volumes and observed data highlights the necessity for up to date, advanced, data driven approach that align evolving technologies and newly emerging failure mechanisms. The first section of the report analyses PV waste estimation using the IRENA 2016 methodology and reviews what has changed since then, considering failure modes, degradation rates, and additional factors.

Evaluating the failure and degradation rates of PV modules is essential for assessing their reliability, economic feasibility, and long-term sustainability throughout their operational lifetime. Moreover, failure rates serve as a foundational input for projecting the expected service life of PV modules and estimating the future volume of end-of-life PV waste. By quantifying how quickly modules deteriorate (degrade) or fail, researchers and policymakers can better forecast replacement needs, plan recycling or disposal infrastructure, and develop strategies to minimize environmental impacts associated with PV system retirement.

Reliability Concerns Amid Rapid Technological Advancements

While emerging PV cell technologies continue to break efficiency records and compete for market dominance, a growing discussion around long term reliability is beginning to come to the surface. This concern stems from the accelerated pace of innovation and the commercialization of new technologies which are being adopted and scaled up rapidly, often becoming mainstream before their failure mechanisms are fully understood. This trend was also observed in previous years within the PV industry. Following the rapid adoption of new materials, processes, and equipment, the years 2017–2018 and 2020 exhibited higher degradation rates compared to more mature periods, (see Figure 2). After 2020, as manufacturing processes became more consistent, defect ratio decreased gradually until 2023. However, in 2023 and 2024, despite the rapid growth of the photovoltaic industry driven by rising demand, the accelerated transition from PERC to emerging technologies combined with the introduction of new materials, larger module formats and designs, and the doubling of global production capacity has brought significant new challenges. These changes have led to a higher failure rate in recent years.

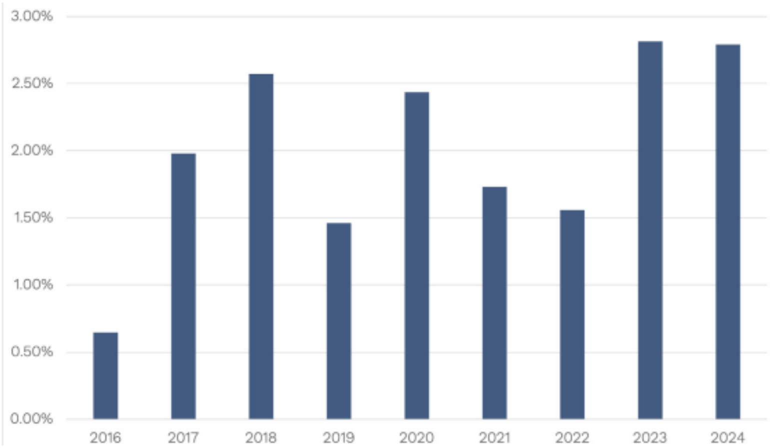


Figure 2. Annual defect ratio, Kiwa PI Berlin's quality assurance data 2025 [5]

Second section of the report provides a comprehensive review of recent findings (2020-2025) regarding observed degradation rates and prevalent failure modes in crystalline silicon photovoltaic (c-Si PV) modules, drawing from peer-reviewed literature as well as industry and laboratory reliability reports. Emphasis is placed on recent degradation mechanisms. The objective is to synthesize information on failure frequencies, degradation rates, and their correlation with factors such as climate, materials, and module design. Lastly, the findings enable a more robust approach to estimating module end-of-life and, consequently, more accurate projections of PV waste volumes.

2 Analysis of PV module collection methodologies

2.1 Review of PV module collection data

The IRENA (2016) report laid the foundation for understanding global PV waste dynamics by issuing cumulative PV waste forecast methodology. In their projections, they adopted the Weibull distribution model. Using historical installation data, typical lifetime assumptions, and paired regular-loss and early-loss scenarios, IRENA issued cumulative PV waste forecast methodology in 2016:

- Regular-loss scenario: Assumes a 30-year lifetime for PV panels with no early failures.
- Early-loss scenario: Includes "infant," "mid-life," and "wear-out" failures before the 30-year lifespan.

For the early loss scenario, the report applied failure rates based on customer complaints and Weibull distribution modelling. Specifically:

- Installation/transport damages (0.5%) - Initial "infant mortality" failures.
- Within first 2 years (0.5%) - Early operational defects
- After 10 years (2%) - Mid-life failures due to material fatigue or environmental stress
- After 15 years (4%) - Accelerated degradation leading to wear-out failures.

The Weibull model parameters were drawn from literature and industry data, with shape factors typically, between 3 and 5 for PV modules. This resulted in an annual failure rate of 0.5%–1% / year during midlife, increasing toward the end of life (see Figure 3) [3].

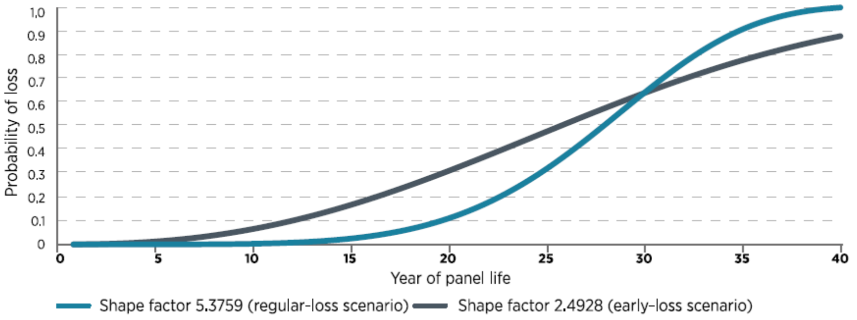


Figure 3. Weibull curve with two different shape factors, IRENA2016 [3]

The study showed that while PV waste is modest in the short term, it will increase dramatically after 2030–2040 as large installation cohorts reach the end of their service life. This study was one of the first global forecasts and provided valuable insight regarding future PV waste volumes. However, these projections do not match the actual PV waste volumes accounted for today. IRENA’s 2016 anticipated 1.5 TWp of installed capacity by 2030, however current capacity has already surpassed 2 TWp. Despite this higher capacity, the expected waste number has not yet appeared in the market. Based on IRENA 2016, Europe (defined according to the regional grouping used in the IRENA 2016) is projected to generate waste of up to 3 million tonnes by 2030. Germany, with an anticipated PV capacity of 75 GW, is forecasted to generate between 400,000 and 1 million tonnes of PV panel waste by 2030. Other significant future PV waste markets include Italy and France. According to Eurostat, 48,395 tonnes of PV module waste were collected from 18 countries in 2022 [4]. Table 1 presents IRENA's 2016 projections for regular and early losses for 2020, along with actual collection data from 2020 and 2023.

Table 1. IRENA 2016 estimates vs. Eurostat actual waste collection data

Country	IRENA 2016 Projection (Regular-loss)-for 2020, tonnes	IRENA 2016 Projection (Early-loss)-for 2020, tonnes	Waste collected at 2020 (Eurostat), tonnes	Waste collected at 2023 (Eurostat), tonnes
Germany	20,000	200,000	15,396	14,186
Italy	5,000	80,000	3,888	30,003
France	1,500	25,000	4,055	5,272
Spain	NA	NA	1,103	4,551
Belgium	NA	NA	1855	1,212
Netherlands	NA	NA	771	1,381

The primary source of this difference is the overestimation of early loss failures, which were assumed to occur at a much higher rate than observed. However, there is no clear indication regarding the breakdown of the collected waste, nor whether it originates from the early or regular stages of the PV module's lifecycle.

Several factors contribute to the discrepancy observed between expected values and actual collection data. Excessive loss assumptions limited historical data, underestimation of technological advancements, improved module durability, as well as customer and market behaviours are key reasons why the numbers do not align. The following section examines these underlying causes in detail:

1. Excessive Loss Assumptions

- Excessive early failure rates

  The 2016 model assumed a significant number of modules would fail prematurely (within 10–15 years). Waste projections were made using assumptions of rapid installation growth and corresponding increases in early retirements; however, the anticipated did not happen. Modules remain in the field longer than expected. There are several reasons for this:

  1. *Performance longevity:* Most modules still deliver ≥80% of their initial power output after 15–20 years, meeting or even exceeding their warranty period. Not all failure mechanisms lead to an immediate loss. Severe glass damage, major junction box failures or delamination generally requires full replacement, with the modules usually being sent to recycling facilities.
  2. *Economic and political factors:* Modules with reduced performance often continue operating due to cost considerations or policy constraints. In addition, industry data indicates that some panel damage can be repaired rather than requiring complete replacement, helping to reduce costs.
  3. *Residential installations:* Owners of residential PV installations often lack the technical expertise or motivation to monitor and analyse PV module performance, which can result in undetected failures

While the failure rate of modules usually follows a bathtub curve, this trend does not directly mean that such modules should be classified as 'waste'. The consideration of repair and the option to sell to the second-hand market should be included in any waste estimation projection. (Figure 4)

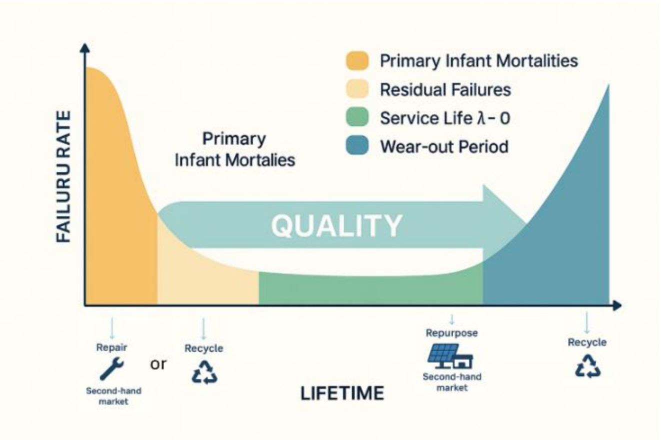


Figure 4. Module failure rate over operational lifetime [7]

- Improvements and better durability

  The end-of-life estimates used in the IRENA 2016 report were based on failure rates reported in the IEA-PVPS 2014 study. The IEA-PVPS 2014 report primarily focused on failure analysis of PV modules, examining data collected between 2000 and 2013. However, in the past ten years, advancements in cells, modules, materials, and production processes, driven by emerging PV technologies, have significantly improved reliability, durability, and performance, surpassing initial expectations. Degradation rate (Table 2) and failure scenarios have changed over time. The previous waste estimation does not account for the learning curve or the potential for rapid improvements.

Table 2. Degradation rates and warranty of PV module manufacturers

Year	First year degradation	Annual linear degradation	Warranty duration
2000 (based on literature [8]		0.8-1%/yr	20 -25 years
2016 (median)	Up to 3%	0.7% / yr	25 years
2024-2025 (median)	1-2%	0.40-0.55%/yr	30 years (many modules)

To achieve more accurate conclusions, we analyse the degradation and failure rates of modules that were deployed earlier, focusing on those examined within the past five years:

Table 3. Comparative table of the oldest PV systems in Europe (>35 years):

Country, Commissioning Year	Module Technology	Degradation Rate	Observation	Ref
Switzerland, 1982	Monocrystalline Si (Arco Solar)	About 21.5% of modules, ~0.2%/year. ~72.9% of modules median rate is 0.62%/year. (2021)	BOM quality critical; many of modules still >80% Pmax. After 35 years, degraded overall module is most by 13%.	[9]
Germany, 1981-1982	Monocrystalline Si (AEG-Telefunken)	~0.5%/year (2020)	Minor delamination, discoloration, junction box aging	[10]
Italy, 2001	Polycrystalline Si (Shell Solar)	0.37%/year (2021)	Water ingress degradation (1 module), minor chalking, discoloration	[11]
Spain,1990s	Monocrystalline	1.4 %/year (2020)	Darkening: 100% Milky pattern: 100% Oxidation: 100% Module with cell cracks: 89,29% Back sheet delamination 21,42% Junction box: 100%	[12]
France, 1992	Monocrystalline	Group 1 (≈33% of modules): Significant decline after 20 years, with an average loss of 33.9% over 31 years (≈1.09% per year). Group 2: More stable performance, aligned with 2012 tests, showing 13% loss over 31 years (≈0.42% per year).	Encapsulant aging and uneven degradation	[13]

Table 4. Comparative Table: Recent studies on modules deployed in the 2000s (15–20 years outdoor exposure)

Country	Module Technology	Exposure duration	Degradation rate	Observation	Ref
USA	Different technologies: Mono/multi c-Si (Al-BSF, PERC,) from Tier-1 manufacturers	9-10 years	0.3–0.5%/year for mainstream modules (Jinko, Trina, Q Cells)	Primarily Isc, and Voc loss. Some of the module experienced glass and cell crack due to hailstorm. Defective inverter	[14]
Germany	Suntech panels	15 years	0.1-0.2%/year degradation	Defective inverter	[15]
Ghana	Different module technologies	5-20 years (majority 10 years)	Median power degradations were m-Si (1.23%/yr), p-Si (1.35%/yr) and a-Si (1.65%/yr).	Encapsulant discoloration, increased series resistance, short circuit current	[16]
Brazil	Monocrystalline	15 years	Average 0.7%/year	Browning (100%), Anti-reflective coating oxidation (100%), Milky pattern (79.2%), cell cracks (27,1 %), back sheet delamination (2,1%), contact corrosion (2.1%)	[17]
France	Polycrystalline silicon (p-Si), and monocrystalline silicon (m-Si)	15 years	p-Si modules exhibited a degradation rate of ≈2% per year, m-Si ≈0,5%/year	Microcracks and inactive cell regions, discoloration, light corrosion, and early signs of delamination.	[18]

South Africa	Monocrystalline	16 years	Annual degradation rate of 1.12 % when taking the specified 3.00% degradation in the first year of operation of the module into account	Burned bypass diode damaging the junction box. All modules show chalking, no back sheet cracks/damage. Age related cell cracks, EVA browning	[19]
Germany	Large rooftop system (Different locations in Germany)	11 years	Average 0.65-0.56%/year	Less than 0.25% was replaced due to defects of PV modules. All most all locations, slight soiling of the PV modules can be seen at edges. The cables ties changed after 3 years later. Inverter failure was main cause of the large fluctuations	[20]

Additionally, further papers were reviewed to assess degradation rates and identify common failure rates. [21-23]

Key Findings:

Degradation Rates: Most modules installed during the 2000s exhibit annual degradation rates of 0.4–0.8%, aligning with global averages. However, exposure to harsh climatic conditions can increase these rates to approximately 1% per year.

Common failure Modes:

- Encapsulant aging (EVA browning/yellowing)
- Back sheet degradation (Chalking, delamination, crack)
- Delamination and moisture ingress
- Corrosion of cell metallization and interconnects, cell cracks
- Junction box failures

Module design, materials, and environmental factors such as temperature and humidity affect long term performance. As observed in Figure 5, failure modes are consistent with those reported in the 2014 IEA PVPS publication. However, modules exhibit higher than expected durability under such failures, allowing them to remain in longer than originally predicted.

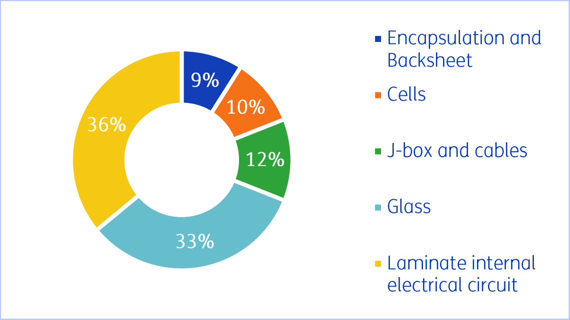


Figure 5. Field study of PV module failures for 8 years, IEA-PVPS 2014 [3]

Another important and common failure is inverter malfunction. While inverter issues do not directly damage the PV modules immediately, they reduce energy yield and can indirectly shorten module lifetime through thermal and electrical stress. The typical lifespan of an inverter is between 10 and 15 years [24,25]. However, studies [14,15,26] have indicated that inverters and cables often require replacement within five years. Such malfunctions may also lead to electrical fluctuations in the PV system.

Despite these failures, PV modules demonstrate greater durability than anticipated, resulting in longer operational lifetimes than initially predicted.

2. PV Owner (Residential Market)

Earlier projections assumed that once a PV module reached its warranty period or dropped below 80% of its original capacity, it would be disposed for recycling. However, in reality, many residential systems remain in use well beyond their expected operational lifetime. This is often due to limited performance monitoring, the lack of economic incentives to replace functioning modules, or the tendency to store old panels rather than dispose of them [27]. As illustrated in Figure 6, studies reveal that more than 80% of consumers have not considered the EoL management of panels, and approximately 60% intend to sell used modules to informal collectors rather than pursue recycling options. Additionally, a significant portion of users believe that managing PV waste should be the responsibility of the government rather than individual owners [27]. When considering the percentage of household installed capacity in Europe, these attitudes may influence significantly the projected amount of waste streams.

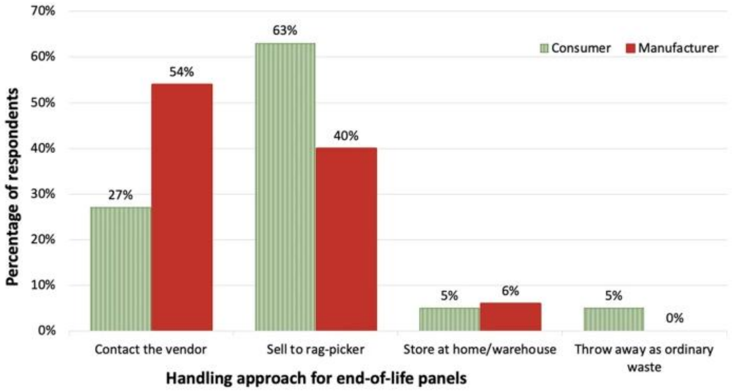


Figure 6. Survey results about handling of end-of-life PV modules, P. Nain et al. [27]

3. Market Behaviour: Repowering & Revamping (Large-Scale)

As PV systems are nearing EoL, plant owners adopt strategies such as repowering and revamping to maintain or improve the performance of solar park. Although there are no official figures for these strategies, market estimation, it is between 500 and 600 MWp / year [28]. Furthermore, by 2030, since most early installed modules will have reached their lifetime capacity, a significant surge in repowering and revamping is anticipated, especially for Germany [29]. For some countries, such as the Netherlands, installed capacity rose sharply between 2019 and 2020. This suggests that there is still time before modules need to be exchanged or sent to recycling facilities. Understanding this market behaviour is also important for the estimation of PV module waste. Previous reports overlooked repowering and revamping to estimate the waste streams; however, current data demonstrates that the figures are significant and should not be disregarded.

Table 5. Waste Impact of Repowering and Revamping

	Repowering	Revamping
Definition	Replacement of components (mainly inverter and modules), with substantially change in plant nominal power	Repair or upgrade of components (mostly inverter and modules), without substantially change in plant nominal power
Impact on waste	It generates significant module waste which can be used for second-hand	

- Second-hand market:

Many modules that are decommissioned earlier than their technical EoL, find a new purpose in second-hand markets, such as in emerging economy countries for off-grid systems, which helps reduce immediate waste generation. Accordingly, two key factors in this context have a significant impact on the projected amount of waste.

Firstly, the second-hand market typically lacks policies defining minimum performance standards for re-sales. Because testing every module to determine the power degradation is costly and impractical, most second-hand modules are sold ‘as it is,’ without verification of remaining capacity and outside of the WEEE directive. Consequently, reaching the guaranteed lifetime of the module does not mean the module will be sent to a recycling facility (Figure 7). Based on our review, some modules available on second-hand websites are over 10 years old. Most of these modules lack labels, serial numbers, or any information regarding their manufacturing date. This is an additional significant consideration that is often neglected when assessing the amount of module waste.

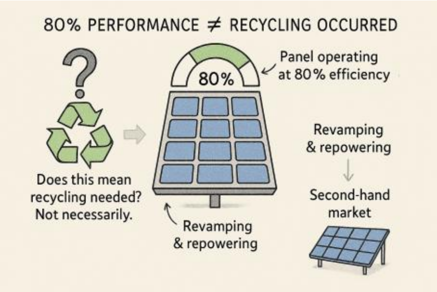


Figure 7. Illustration of PV module recycling decisions

Secondly, not all decommissioned panels are sold domestically. Modules are often exported to Africa, and Asia for reuse, a lucrative alternative to the WEEE regulation. Here, we are facing a high risk of losing panels, which directly impacts the projected volume of module waste and the availability of primary raw materials in Europe (Figure8) [30].

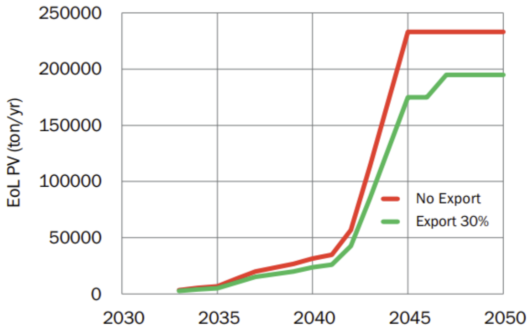


Figure 8. Projected yearly volumes of PV waste, TNO [30]

At present, PV modules sold for reuse are primarily obtained from large commercial PV systems PV plants (exceeding 1MWp) located in Europe, the USA, and China [28].

- Local regulations

  Country or region-specific forecasts yield more accurate projections, as each nation has its own energy transition strategies, growth trends, installation rates, and waste management practices. Regions with strong regulations, like the EU, predict higher recycling rates and less landfill waste. In contrast, the lack of unified rules in the U.S. could lead to 20 million tonnes of PV waste landfilled by 2050, while the EU aims for most waste to be recycled under WEEE standards [31]. Clear regulations encourage investment in recycling infrastructure. Nations such as Japan, South Korea, and those in the EU that have mandatory take-back programs are establishing specialised PV recycling plants, leading to better waste management predictions [4].

While IRENA 2016 provided a valuable overview for estimating PV module waste quantities, its projection method had limitations due to the lack of historical data, exclusion of the second-hand market and policies, assumptions of improved reliability, and lower expectations for PV panel lifespans. IEA PVPS 2022-2025 [4-32] revisits these projection methods by using the Weibull distribution, but this time, carefully considering technological advancements as well as local regulations, and policies to match the local conditions in each country or region (see Table 6).

Table 6. Comparison of PV Module Waste Stream Estimation Methodology

IRENA 2016 - Projection method	IEA-PVPS 2025 – Projection method
• Weibull-based mass flow, two fixed scenarios (early vs regular loss) • Assumes modules last 30 years, then drop to zero. • Includes an early-loss scenario (10% fail by year 15). • Reuse/repowering ignored. • Policy influences minimal. • Limited historical data on long-term performance	• Lifetime 35 years • Empirical and modelled with real waste data • Reuse and repowering included. • Incorporates degradation rates, repowering trends, and technological improvements

3 Failure rates analysis of photovoltaic modules

To gain insight into recent technology failure rates, both accelerated test programs and field data are valuable sources of information. However, many newly commissioned modules in the field lack well-established long-term failure rates. While publicly available field data from the past five years is limited, several studies and outcomes from independent test laboratories provide insights into field degradation and failure modes.

3.1 Recent Technologies: Degradation & Failures

The latest scorecards and studies provide compelling evidence of growing concerns regarding PV module reliability. According to Kiwa PVEL's 2025 edition of the scorecard, as illustrated in Figure 9, the highest failure rate in the past five years was recorded. The findings indicate that the primary causes of degradation are linked to Mechanical Stress Sequence (MSS) and Hail Stress Sequence (HSS) tests. [33]. Compared to TÜV Rheinland's 2016 report, the dominant failure mechanisms have shifted from issues primarily identified through climate chamber testing to those revealed by mechanical stress testing. Historical data from 2005–2009 and 2006–2013 indicate that the most critical tests for crystalline silicon PV modules were the temperature cycling test, damp heat test, and humidity freeze test [34].

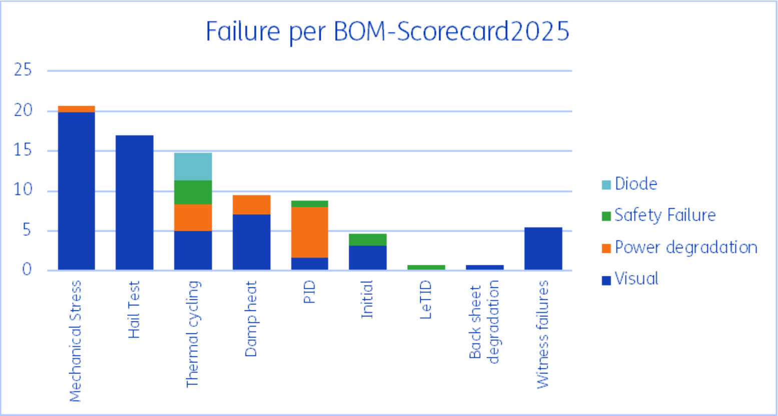


Figure 9. Kiwa PQP, test lab failures 2025

Another point highlighted in the multiple reports [5,35] is quality concerns: some modules exhibit significant manufacturing defects that prevent them from being shipped. These defective products not only impact performance but also raise serious reliability and safety issues.

Even though accelerated laboratory aging tests provide valuable insights for evaluating the modules before deployed, they do not fully replicate the real-world failure risks due to the complexity of field conditions. Therefore, field data from the past five years was reviewed to assess the failure rates of PV modules. Table 7 presents the degradation rates of modules deployed over the past five years, with a specific focus on those classified as modern module technology.

Table 7 – Representative field degradation rates of c-Si PV modules (2020–2025)

Study/Region	Module-technology	Observed degradation rate	Observations	Ref
NREL-USA-	Sunpreme n-HIT (bifacial) (deployed at 2019)	2%/yr power loss	Front side Isc decreased. UV degradation and PID-p was observed	[14]
NREL-USA	Longi mono perc & mono perc bifacial (2020)	0.25%/yr power loss	After two years, the modules showed significant power drops	[14]
Kiwa PI/ Solyco-Germany	n-type TOPCon modules from November 2023 to September 2024	Up to 2.4% power loss after 9 months in ground-mounted field test.	Power loss due to UV degradation	[36]
Duramat & Kiwa Study	Different module technologies (TOPCon &HJT, PERC with varies number of busbars and cells). Samples have variety of cracking stress, from 0% to 100% cracked cells	Degradation rate varies by bill of material (BOM) between −0.8%/yr and −3.3%/yr.	A significant decrease in open-circuit voltage is observed during the initial five months of deployment. Cell crack shows minor effects on power production	[37]
DTU -Denmark	Huawei Bifacial p-PERC, glass-glass (different type of modules), April 2021-August 2023	Mean value 0.63% power loss in two years	Potential PID (p- or c-type), weak cell interconnections, finger contact failures, line cracks	[38]

US Department - Sandia National Laboratories (3-4 years field data)	Canadian Solar-Monoperc-5 busbars (deployed 2018), LG Mono pert-12MBB (deployed2018); Panasonic (N-type SHJ, 4bb)	Degradation rate(%/year) Canadian 1.03%, LG 0.23%, Panasonic 0.75%	Primarily voltage-related losses and fill factor (FF) losses.	[39]
Case study-India (2 years)	Monocrystalline	1.05 %	Hot spot formation, glass cracking, junction box failures & swelling	[40]
Fiel data study in desert climates, 3 years	different module technologies (SHJ, TOPCon & PERC)	Highest relative Pmax loss for SHJ 8.73%, 2.17% for TOPCon	Severe delamination for some of the SHJ modules. Loss in open-circuit voltage and short-circuit current.	[41]

Recent field data indicate that degradation rates for modern silicon PV modules (2020-2025) typically range from 0.3% - 2% per year, depending on the technology, manufacturer, and climatic conditions. Compared to earlier PV deployments, some modules exhibit a higher degradation rate, indicating an increased reliability concern. When compared with companies' warranty data, as presented in Table 8, field measurements indicate slightly higher degradation rates.

Table 8 – Degradation rate according to Top Tier's most recent product datasheet

Technology	First year degradation	Annual degradation
PERC	2%	0.45-0.55% per year
TOPCon	1%	0.40-0.45% per year
HJT	1%	0.25-0.30% per year
xBC	1%	0.35% per year

Our review focuses mainly on PV modules deployed in the field for of utility scale, since they are the mostly reported on or researched common. We did not consider the specific failure modes for PV modules installed on buildings (BIPV or BAPV), on vehicles (VIPV), floating structures on lakes or seas (FPV), or agricultural PV (Agri-PV) systems. The failure modes of PV modules can vary or accelerate depending on specific stressors and climatic factors. Early and frequent loss scenarios can change, particularly in more severe climate conditions.

In the following section, we delve into most recent and relevant failure modes, to understand higher degradation rates which have changed alongside module technology advancements, observed in the field and their impact on module reliability.

3.1.1 Cell cracking and hotspot

Based on recent research, the occurrence of cell cracks is commonly associated with mechanical stresses introduced during cell processing such as cutting cells into half-cut or third-cut formats as well as during string assembly and other module manufacturing steps [6]. According to manufacturing audit data 2024 [5], cell cracking represents one of the highest failure rates observed in PV module production.

According to a clean-energy advisory firm (Clean Energy Associates, CEA), a global survey (148 sites, approx. 300,000 modules) showed exceedingly high prevalence of microcrack-related defects:

- 83% of sites had line cracks.
- 78% had soldering anomalies.
- 76% had complex cracks.

According to this survey, there was a sharp rise in cracks during the first half of 2023 as shown in Figure 10. CEA data suggests many defects come from manufacturing, but also occur during transport, installation, and operation [43].

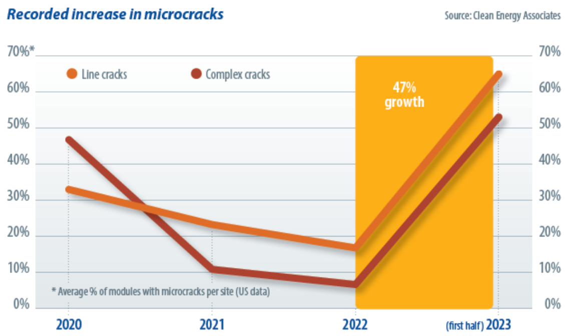


Figure 10. Recorded increase in microcracks (Clean Energy Associates, 2024)

To understand how cracked cells affect PV module performance in the field, several studies have been conducted. Findings indicate that in older modules characterized by thicker cells, glass/back sheet construction, and 3–5 busbars microcracks had a measurable impact on power output. For polycrystalline technology, power losses due to microcracks ranged between 0.82% and 3.21%, with variations depending on whether the module was stored in a facility or actively operating in the field [44]. In monocrystalline technology, losses were lower, between 0.55% and 0.9%, although some samples from both technologies exhibited additional defects beyond microcracks, leading to more severe performance degradation. Another study reported approximately 0.2% power loss per dendritic-like cracked half-cell in modules using multi-wire Passivated Emitter and Rear Cell (PERC) technology. In addition to that, recent research on modern silicon technologies such as HJT and TOPCon with 6 to 20 busbar designs suggests that cell cracks are no longer a major performance concern. Recent studies found no evidence of additional degradation mechanisms over time attributable to cracks in these advanced module designs [37,42].

Once deployed in the field, cracked cells can create localized areas of elevated temperature, known as hot spots. Hot spot formation can accelerate several failure mechanisms within the module, including polymeric encapsulant degradation, back sheet deterioration, and delamination. Under extreme thermal stress, hot spots may even contribute to junction box detachment or degradation of electrical interconnects. It is important to note that hot spots can also arise from non-manufacturing factors, such as partial shading, soiling, or modules with long substring layouts that increase current imbalance risk. However, ongoing advancements in solar cell architecture (multi busbar and half cut cell design), module design (split diode approach), materials, and quality control processes have reduced the severity and frequency of cell crack related hot spots observed in the field in recent years compare to previous years.

3.1.2 Light induced degradation (LID) & Light and elevated temperature induced degradation (LeTID)

While failure modes related to module design tend to show an increasing failure rate trend, cell level degradation phenomena such as Light-Induced Degradation (LID) and Light- and Elevated-Temperature-Induced Degradation (LeTID) have demonstrated improvement. LID and LeTID are types of cell degradation that play a major role in power loss, especially in p-type Al BSF and PERC solar cell modules [42]. LID typically causes the most significant performance loss within the first few hours of light exposure (early life degradation), often amounting to several percent relative to the initial module output. In contrast, LeTID continues to occur over time at elevated temperatures throughout the module's lifetime. After the degradation phase, both phenomena can exhibit a slow recovery. However, this recovery is often difficult to quantify in the field due to the influence of other degradation mechanisms and varying climatic conditions.

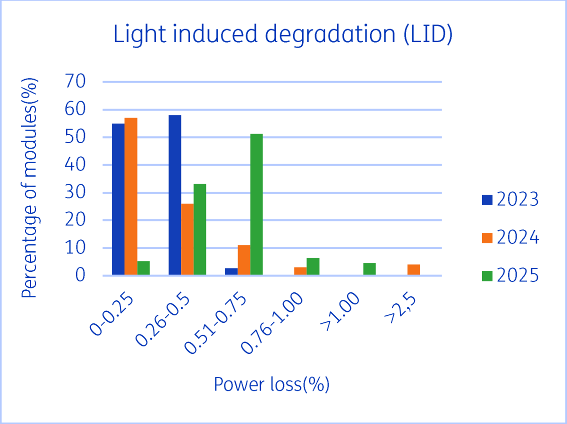


Figure 11. LID degradation based on RETC PV module index reports

Accelerated laboratory test reports indicate a downward trend in LeTID and LID degradation, primarily due to advancements in solar cell technology and manufacturing processes, see Figure 11 [45-47].

3.1.3 UV-ID degradation

Although TOPCon, HJT, and n-type PERC solar cell technologies have improved in performance, they have also raised reliability concerns. Recent findings indicate that especially TOPCon and HJT solar cells exhibit significant degradation under accelerated UV exposure. Based on Kiwa reports, after UV testing more than 80 bills of materials (BOMs), the median power loss observed was 3.1% for TOPCon and 4.2% for HJT modules, compared to 2.2% for PERC modules. Multiple failure mechanisms associated with UV-induced degradation (UV-ID) were observed concurrently across different cell types, highlighting the complex nature of this degradation mode [48].

To assess the performance of modules in real-world conditions, additional case studies are necessary. A recent study reported severe degradation of n-PERT modules at a utility-scale plant, with losses reaching 2.4% per year based on two primary mechanisms: (1) cell surface recombination losses caused by UV-ID, and (2) increased series resistance (Rs) in cells with metallization paste compositions susceptible to encapsulant degradation [49]. Another 3.8 years outdoor study indicates that TOPCon modules are more most sensitive to UV degradation and show more than 7% relative efficiency loss with the Voc as the main contributor [50].

UV degradation was already examined in the early years (2011–2016) on PV modules, with a focus on power losses and polymeric component failures such as encapsulant and back sheet degradation. However, UV-ID was not highlighted in the PVPS 2016 report, as the most common failure for silicon-based PV modules. UV-ID is one of the significant failure modes observed in the field, raising serious concerns about long-term reliability and module warranty commitments.

3.1.4 Potential-induced degradation

Potential-Induced Degradation (PID) has been one of the most widely studied degradation mechanisms in PV modules for over 15 years. Recent research has shed light on additional degradation types, broadening our understanding of module reliability: PID-Corrosion, PID-Delamination, PID-Penetration, PID-Polarisation, and PID-Shunting [6, 42].

Although multiple forms of PID exist, PID-polarization (PID-P) is currently the most significant and emerging degradation mode affecting all major cell technologies. According to PVEL reports, there is no clear advantage among cell types TOPCon, PERC, and HJT exhibit similar susceptibility to PID-P. The 2023 Scorecard indicates that the median PID-P degradation across modules was approximately 1.8%. When broken down by cell technology, the median power loss remained in a comparable range: around 1.6–2.0% for both PERC and TOPCon [51]. However, field performance data tells a different story (see Table 9). Aging and secondary degradation pathways such as UV-induced defects, moisture ingress, and encapsulant material choices can amplify PID-P risk over the time.

Table 9. Overview of field PID degradation studies

Period	Test type	Degradation rate	Ref
2023	Field-representative (PID-P)	Under UV + moisture conditions: ~3% degradation and under extreme conditions (-1000 V, 60°C, 96 h, dark): up to 30% power loss	[52]
2018	1 year Field data	Highest degradation of power is 53.26% and lowest 1.79%	[53]

Although advancements have been made, PID continues to be the primary contributor to significant power losses in PV modules, as indicated by accelerated test reports [34,54].

3.1.5 Encapsulant and back sheet degradation

Until 2020, ethylene-vinyl acetate (EVA) was the dominant encapsulation material in photovoltaic (PV) modules due to its cost effectiveness and proven reliability. However, several technological and market developments have led to varieties in encapsulation strategies, (see in Figure 12):

- Shift to Glass-Glass Modules
- Advancements in cell technologies: the increasing adoption of TOPCon and heterojunction (HJT) have increased sensitivity to certain encapsulation materials.
- Busbar design in cell technologies: shifting to multi busbar and zero busbar, changing the thickness of encapsulant.

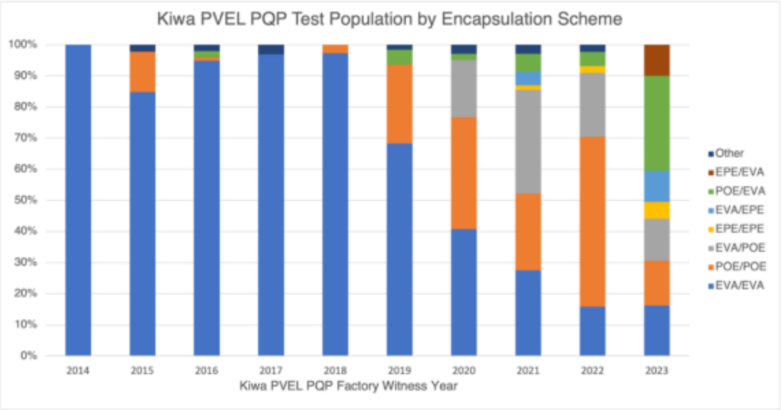


Figure 12. A graph illustrates the evolution of encapsulation schemes by Kiwa. [55]

As shown in Figure 12, Ethyl Vinyl Acetate (EVA) can be applied to either the front side, the rear side, or both sides of the module. Moreover, in the EPE structure (EVA–POE–EVA), EVA continues to be widely used, which reinforces its position as the leading choice in the market (Figure 13) due to its broad recognition and cost-effectiveness. By adding UV cut-off agents and other additives, EVA has been enhanced to address issues such as discoloration and PID degradation.

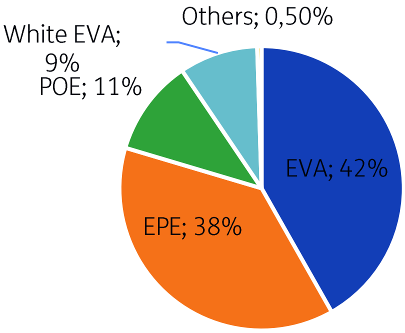


Figure 13. Market share of encapsulant 2024/2024, (TaiyangNews 2025 [56])

Recent encapsulant designs are also intended to reduce common forms of degradation observed in the field. Studies indicate that nearly all modules deployed 5–10 years ago exhibit yellowing or browning as a result of acetic acid formation from ethyl vinyl acetate (EVA). While traditional discoloration degradation (yellowness and browning) of encapsulant may be less likely in newer encapsulants, novel degradation pathways could emerge due to unknown field effects of new encapsulants and their combinations. Recent laboratory research shows that solar cell technologies with different encapsulant types may experience varying levels of UVID or PID degradation. However, no definitive degradation mechanism has been established in the field for new encapsulant materials.

Additional reliability concerns may arise from the interaction between encapsulants and back sheets, including material incompatibility and delamination, which can significantly increase failure rates. Furthermore, exposure to ultraviolet radiation, thermal aging, hotspots, and manufacturing defects may result in delamination and cracking of the back sheet. Cracks can often be repaired using specialized tapes or coatings. Other issues, including bubbles, discoloration, and chalking, do not have an immediate impact on module performance. Delamination and crack formation typically occur after several years of field aging, and recent field reports and laboratory test reports indicate low failure rates attributable to back sheet degradation [6]. Laboratory test results indicate a decreasing trend in back sheet degradation. Additionally, recent field data show no clear evidence of degradation.

3.1.6 Glass breakage

The high failure rate was primarily attributed to mechanical stress, hail impact tests, and thermal cycling sequences. Mechanical stress and hail tests are critical for evaluating the reliability of glass and frames under extreme weather conditions such as heavy snow, hail, and high winds. Failures in these tests typically involve glass or frame breakage, and in some cases, extensive glass cracking. While cracked glass does not immediately result in power degradation, hot spots, or cell cracks, it poses a significant long term reliability risk. Over time, broken glass substantially increases the likelihood of further damage and system failure.

There are two main reasons for increasing glass breakage in the field:

1. Module: Glass-glass structure, thinner glass
2. Mounting: Heavier glass, unchanged mounting points (see Figure 14.) [57]

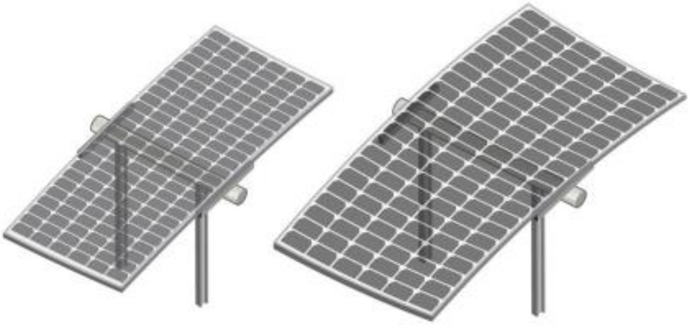


Figure 14. Larger module and unchanged mounting structure, NREL [57]

Recent reports indicate a significant shift toward glass-glass (G//G) modules over the past two years, driven by several factors. One major reason is the growing adoption of bifacial solar cell technology. Another key driver is the emergence of advanced cell technologies such as TOPCon and HJT, which are more sensitive to water vapor transmission compared to PERC and Al-BSF cells. These developments have accelerated the transition from glass-backsheet (G//BS) to glass-glass(G//G) designs, see Figure 15.

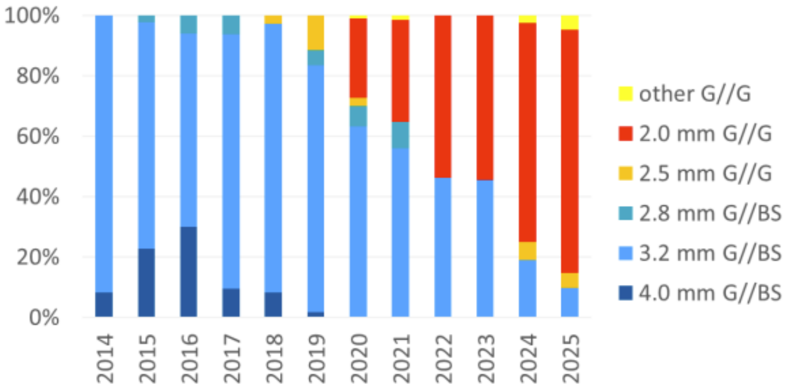


Figure 15. Solar glasses thickness by module type based on Kiwa PVEL PQP test population [58]

However, as modules have become larger and heavier, manufacturers have reduced glass thickness compared to previous years. According to ITRPV 2025, glass thicknesses of 2–3 mm have become increasingly common within the industry, with a notable trend among module manufacturers toward incorporating 1.6 mm thickness glass into their product portfolios as depicted in Figure 16.

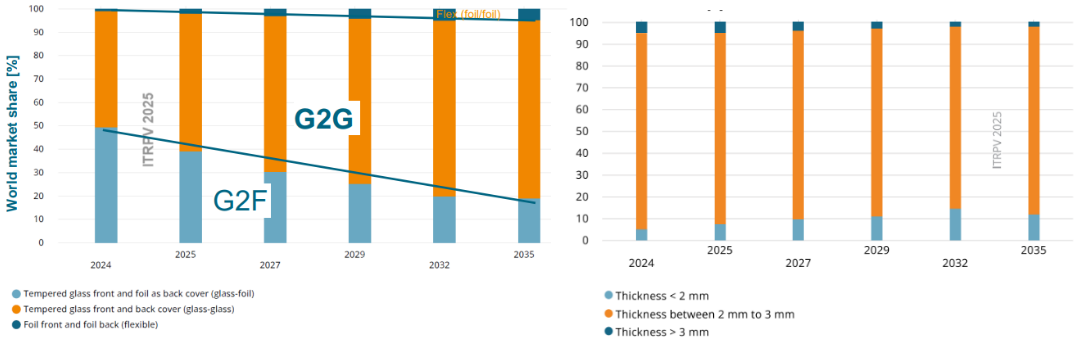


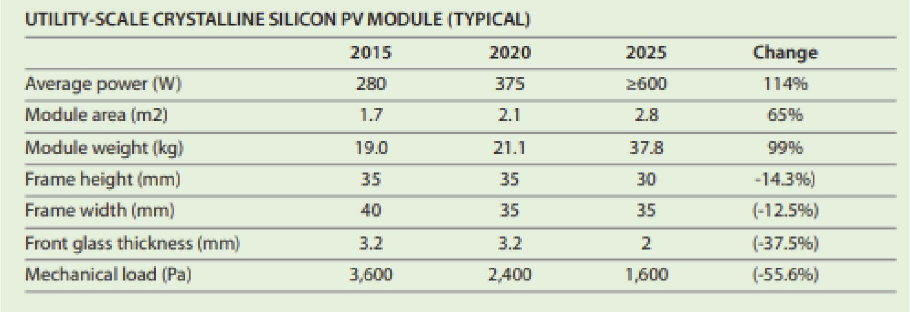
Figure 16. Market share of glass/glass module structure and glass thickness, ITRPV2025 [2]

As the thickness of solar glass decreases over time, its reliability also decreases. Test results reveal that 2-2 mm glass-glass modules exhibit lower reliability than 3.2 mm glass-backsheet modules in mechanical stress and hail impact tests. Thinner glass combination with reduced glass manufacturing quality, larger module dimensions, frame interactions, edge pitch effect, wrong mounting and installation practices and climate effects collectively contribute to higher breakage field rates in field [59].

A recent study of Fotovoltaica-UFSC project in Brazil, set up a large size bifacial silicon PV module to evaluate their performance. Unexpectedly, frequent glass breakage became a focus: within nine months, over half the modules had cracked glass, averaging fourteen broken modules per month, see Figure 17.

Figure 17. Fotovoltaica-UFSC case study, 2023 [60]

As Figure 18 demonstrates, when the modules increase in size and weight, the mounting structures tend to become weaker [61]. Additionally, the number of mounting points often remains unchanged even as the module design grows larger. This leads to increased stress on both the frame and the glass. As seen in Fotovoltaica-UFSC project study, these incorrect mounting systems can cause glass cracks even in not particularly harsh climate conditions.



UTILITY-SCALE CRYSTALLINE SILICON PV MODULE (TYPICAL)

	2015	2020	2025	Change
Average power (W)	280	375	≥600	114%
Module area (m2)	1.7	2.1	2.8	65%
Module weight (kg)	19.0	21.1	37.8	99%
Frame height (mm)	35	35	30	-14.3%)
Frame width (mm)	40	35	35	(-12.5%)
Front glass thickness (mm)	3.2	3.2	2	(-37.5%)
Mechanical load (Pa)	3,600	2,400	1,600	(-55.6%)

Figure 18. Table of utility scale c-Si PV module design trends, Pvtech 2025 [61]

While earlier reports indicated that about 0.5% of PV panels experienced glass breakage during transportation and installation, recent findings show that glass breakage also occur during manufacturing (from edge pinch), within the first year due to improper mounting, or later through severe weather. In addition, documented cases show that in some thin-glass (≤ 2 mm) G/G modules, 5–10% of rear glass breakage occurred within the first two years of operation. Over the lifetime of PV module, degradation can accelerate following glass breakage because of moisture ingress, delamination, cell cracks, and hot spot formation.

3.1.7 Junction box related failures

Junction box failures can lead to early module failure, reduced energy yield, or even system downtime. If there are unreliable connections in the junction box, connection failures occur in the junction box within one and two years of installation, see Table 10.

Common degradation mechanisms include solder joint failures, bypass diode malfunctions, corrosion from moisture and dust ingress, adhesive or tape deterioration, and mechanical fatigue from thermal cycling or environmental loading. These failures can lead to open-circuit conditions, hotspots, and even fire hazards.

Table 10. A review of junction box failures throughout the years

Study/Region	Failures	Ref
Global Field Database (1 GW, 3.8M modules) (2014-2018)	Failure rate: 19.2 ppm in first 5 years (2014–2018) Main causes: burnt bypass diodes, burnt junction boxes, poor welding. 85% failures due to installation errors	[62]
PVEL-Field case 2023 results, Taiwan (2 years)	0,2% diode, 0,029% burned j-box, 2% hot spots at Junction box	[63]
PVEL 2024 Scorecard	%17 junction box falling, 11% wet leakage/safety failure %8 bypass diode failure, %6 melted/damaged connectors	[37]
Field study/Indonesia-less than 2 years operational (64,140module), 2025	0,1% junction box falling	[64]

Most of these failures are caused by manufacturing defects and can often be detected during end of production or pre shipment inspections. Over the lifetime of PV modules, junction boxes may experience one or more malfunctions. Based on field observations, these junction boxes can either be repaired or replaced.

3.1.8 Other failures

In this report, we focus on the most relevant failure types observed in the field. Emerging technologies such as TOPCon and HIT have demonstrated increased issues and degradation mechanisms in both laboratory and field studies. In addition to the previously mentioned degradations, examples include metal contact degradation, paste-related degradations, Indium tin oxide (ITO) corrosion, and flux-induced degradation. These failures often accelerate or interact with other failure mechanisms, leading to greater effects. For a detailed overview, the IEA PVPS 2025 report provides comprehensive information on degradation mechanisms [6].

3.1.9 Climate Conditions

Climatic conditions significantly influence the degradation mechanisms of PV modules. Various studies [65-66] have investigated environmental stressors such as elevated temperatures, high humidity, solar irradiance, hurricanes, wildfires, and hailstorms as contributing factors to degradation rate. Photovoltaic panels operating in hot climates exhibit an annual degradation rate that is 0.5% to 1% higher than those in moderate environments.

Recent modelling by researchers at UNSW [67] underscores the need to consider a warming climate in PV module design. Their findings suggest that future PV modules could experience up to 12% greater power loss due to accelerated degradation. The study revealed that degradation rates are significantly higher in hot and humid regions, such as northern Australia, compared to central Australia, where drier conditions and lower humidity result in smaller increases in degradation, see Figure 19 [67].

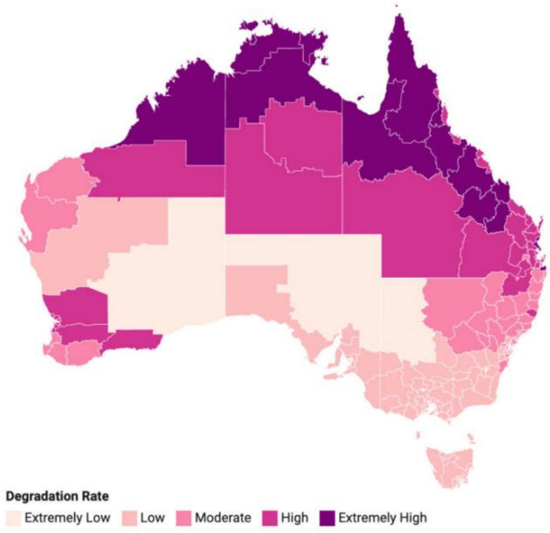


Figure 19. PV module degradation rate in Australia, pvmagazine-australia 2024[68]

Hailstorms account for approximately 0.2% of panel failures each year, with the majority occurring in regions such as the United States [69-70]. Another study [71] reports that hail events between 1990 and 2017 predominantly occurred in the southern regions of the Netherlands. With projections indicating an increase in both the frequency and intensity of hailstorms, PV modules and other exposed components are expected to face an elevated risk of impact-related damage in the future. Consequently, when defining the failure rates of PV modules, it is important to consider the climate conditions of the region.

3.1.10 Comparison of failure rate scenarios

Based on a review of current literature, we present early and regular loss scenarios for modules manufactured within the last five years, using data from independent laboratory tests, field observations, published studies, and manufacturer feedback. These scenarios are compared with those outlined in the IRENA 2016 report.

	Scenario	Failures (Based on IRENA2016)	Failures (Based on current research)
Early Loss	Installation/transport damages - Infant mortality	LID (observed in 0.5%-5% of cases), poor installation, junction boxes, string boxes, charge controllers, cabling and grounding	Glass breakage, poor installation, junction box failures, (Note: Depending on the type of failure, the junction box may be repairable.)
	Within first 2 years - Early operational defects	Degradation of anti-reflective coating of the glass, discoloration of the EVA, delamination and cracked cell isolation	Glass breakage, junction box failures (Note: Depending on the type of failure, the junction box may be repairable.)
	After 10 years – Midlife failures	Mechanical load cycles (e.g. wind and snow loads) and temperatures changes - include PID, contact failures in the junction box, glass breakage, loose frames, cell interconnect breakages, and diode defects	Mechanical load cycles (e.g. wind and snow loads) and climate effects including PID, LeTID, UV-ID, junction box failures, contact failures in the junction box, glass breakage, loose frames, cell interconnect breakages, cell breakage, hotspot, encapsulant and back sheet degradation(discoloration and delamination) (Note: Not all midlife failures result in early loss)
	After 15 years-Wear out	In the wear-out phase, failures similar to those observed during the midlife phase increase exponentially, accompanied by severe corrosion of cells and interconnectors	Midlife phase failures increase exponentially
Regular Loss	• 30-year average panel lifetime • 99.99% probability of loss after 40 years • Initial losses and early losses are excluded		• 35 years average panel lifetime [4] • Although LID, LeTID, PID, and UVID degradation effects appear during early operation, this does not mean the module will be considered as 'lost' at that stage. •Forecasting approaches (approximately 30% export of PV modules)

4 Recommendation for Estimating EoL PV module Waste

Accurate estimation of PV module waste requires consideration of several parameters, including installed capacity and growth trends, module lifetime distribution, technological advancements, degradation and failure rates, as well as market and economic factors. Furthermore, waste projections should be disaggregated by region and by installation type (e.g., residential versus utility-scale), creating a predictive modelling hypothesis.

In the predictive modelling hypothesis graph for the Netherlands, which incorporates both early-loss and regular-loss forecasting approaches and 30% export of PV modules outside of the Netherlands, the shape factor (α) values applied are 2.4928 for the early-loss scenario and 5.3759 for the regular-loss scenario based on IRENA. These shape factors are determined through regression analysis, utilizing data points sourced from existing literature and early failure scenarios. Nevertheless, it is recognised that these values may represent overestimations. When applying a Weibull modelling approach, it is essential to integrate up to date technical and non-technical data.

- Technical Aspects:

Key factors influencing lifetime assessment include the impact of degradation and failure mechanisms on early-loss scenarios, technological advancements, and climatic conditions. For example, the Netherlands is classified as a temperate climate region; therefore, degradation and failure rates must be defined based on conditions typical of such regions.
The majority of PV module failures occur within the first 2–3 years, primarily due to manufacturing defects or installation errors. Beyond this initial period, failure rates decline sharply, with annual failure rates typically falling below 0.1% during years 5–25 of operation (based on current study).

- First years (including transportation and installation losses) (0–5 years): 0.3% – 0.8% of PV module affected
- Midlife degradation (5–25 years): 0.1% – 0.5% of PV module affected

- Non-technical influences:

When defining PV module lifetime, additional factors such as repowering, end-of-contract decisions, second-hand market dynamics, user behaviour, and PV module export scenario should be considered. These economic drivers and market parameters can significantly influence waste generation, impacting both the timing and volume of PV module decommissioning.

Figure 20 illustrates the early loss (depicted by the blue line) and regular loss (represented by the orange line) of PV module. Based on this research, the probability of PV module failure is estimated to fall between the regular-loss and early-loss scenarios, as illustrated in Figure 20. The hypothesis-based waste modelling approach (depicted by the green line) is generated by adopting the Weibull distribution.

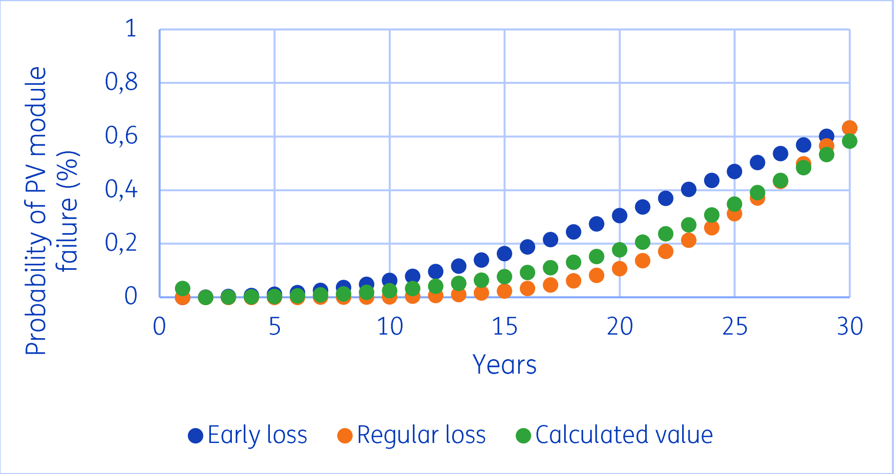


Figure 20. Weibull distribution for PV waste scenarios, based on 30-year average panel lifetime, IRENA2016

This study provides a hypothesis-based waste modelling approach for PV modules. To achieve more realistic waste projections, it is essential to integrate multiple influencing factors, including technological advancements, evolving failure modes, new module designs and their associated reliability profiles, repowering and revamping strategies, second-hand market dynamics, regulatory frameworks, installation practices, and user behavior. Several sources [6] provide estimates regarding the future volume of PV module waste. However, precise predictions are challenging due to the multitude of influencing factors.

Using this hypothesis-based modelling approach , the projected waste from PV installations in the Netherlands has been calculated, see Figure 21, assuming that 30% of the modules are exported outside of the Netherlands.

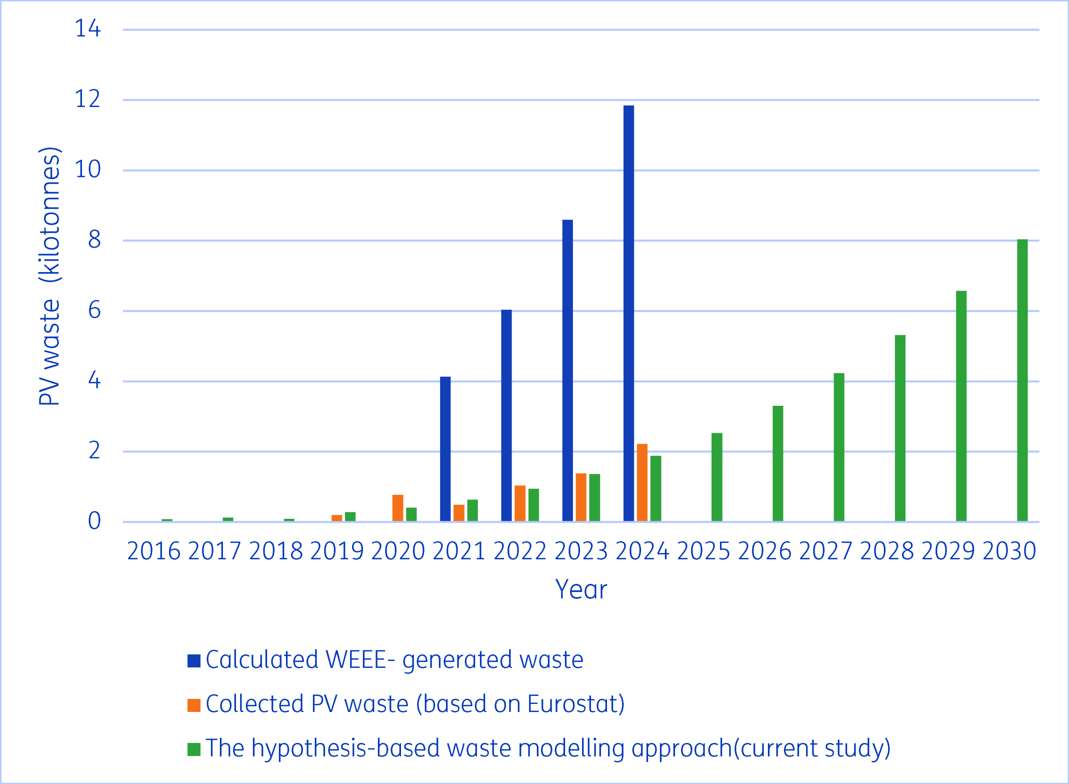


Figure 21. Yearly PV module waste in Netherlands (kilo tonnes), covering PV installations from 2003 to 2030 (Data from Eurostat(2003-2023) & Solar Power Europe)

The hypothesis-based waste modelling approach for yearly PV module waste demonstrates strong alignment with actual collected data from Eurostat. However, for future analyses, it is essential to recognize that accurate PV waste forecasting requires a region-specific, data-driven methodology that also considers installation type (residential or utility scale). The approach should integrate both technical and non-technical drivers. As previously noted, PV module technologies continue to evolve. The new methodology should account for new module designs, longer module lifetimes, enhanced reliability, and the significant influence of second-hand markets and export practices. Therefore, it is recommended to revisit the modelling approach, incorporating newly available data. By adopting these recommendations, stakeholders can develop more realistic strategies for circular economy planning, recycling infrastructure, and sustainable management of PV module waste.

5 References

[1] VDMA Photovoltaic Equipment, International Technology Roadmap for Photovoltaic (ITRPV): Results 2016, 8th ed, 2017.

[2] VDMA Photovoltaic Equipment, International Technology Roadmap for Photovoltaic (ITRPV): Results 2024, 16th ed, 2025.

[3] International Renewable Energy Agency (IRENA), REmap: Roadmap for a Renewable Energy Future, 2016 Edition. IRENA, 2016.

[4] K. Komoto, C. Agraffeil, C. Alonso-Garcia, D. Costa, T. Curtis, A. Danelli, and R. Woods-Robinson, Status of PV Module Recycling in IEA PVPS Task 12 Countries, IEA Photovoltaic Power Systems Programme, 2025.

[5] Kiwa PI Berlin, The 2025 PV Module Manufacturing Quality Report. Kiwa, 2025. [Online]. Available: https://www.kiwa.com/globalassets/usa/pi-berlin/resources/kiwa-2025-pv-module-manufacturing-quality-report.pdf

[6] M. Köntges, J. Lin, A. Virtuani, G. C. Eder, G. Oreski, P. Hacke, and E. Özkala, Degradation and Failure Modes in New Photovoltaic Cell and Module Technologies, Report IEA-PVPS, 2025.

[7] PV Tech, “The land of rising risk,” PV Tech Power, vol. 23, pp. 24–29, 2019.

[8] D. C. Jordan and S. R. Kurtz, “Photovoltaic degradation rates—an analytical review,” Prog. Photovolt. Res. Appl., vol. 21, no. 1, pp. 12–29, 2013.

[9] A. Virtuani, M. Caccivio, E. Annigoni, G. Friesen, D. Chianese, C. Ballif, and T. Sample, “35 years of photovoltaics: Analysis of the TISO-10-kW solar plant, lessons learnt in safety and performance—part 1,” Prog. Photovolt: Res. Appl., vol. 27, no. 4, pp. 328–339, 2019.

[10] SolarGrid, The Oldest Photovoltaic Array in the World Still in Operation, Oct. 15, 2020. [Online]. Available: https://solargrid.pk/2020/10/15/the-oldest-photovoltaic-array-in-the-world-still-in-operation/

[11] C. Del Pero, N. Aste, F. Leonforte, and F. Sfolcini, “Long-term reliability of photovoltaic c-Si modules – A detailed assessment based on the first Italian BIPV project,” Solar Energy, vol. 264, p. 112074, 2023.

[12] L. Lillo-Sánchez, G. López-Lara, J. Vera-Medina, E. Pérez-Aparicio, and I. Lillo-Bravo, “Degradation analysis of photovoltaic modules after operating for 22 years: A case study with comparisons,” Solar Energy, vol. 222, pp. 84–94, 2021.

[13] [10] PV Magazine, Solar Modules Deployed in France in 1992 Still Provide 75.9% of Original Output Power, Jun. 7, 2024. [Online]. Available: https://www.pv-magazine.com/2024/06/07/solar-modules-deployed-in-france-in-1992-still-provide-75-9-of-original-output-power/

[14] C. Deline, D. Jordan, B. Sekulic, J. Parker, B. McDanold, and A. Anderberg, PV Lifetime Project – 2024 NREL Annual Report, NREL/TP-5K00-90651, National Renewable Energy Laboratory, Golden, CO, USA, 2024.

[15] P. Olczak, “Evaluation of degradation energy productivity of photovoltaic installations in long-term case study,” Applied Energy, vol. 343, p. 121109, 2023.

[16] B. Aboagye, S. Gyamfi, E. A. Ofosu, and S. Djordjevic, “Degradation analysis of installed solar photovoltaic (PV) modules under outdoor conditions in Ghana,” Energy Reports, vol. 7, pp. 6921–6931, 2021.

[17] J. E. F. da Fonseca, F. S. de Oliveira, C. W. M. Prieb, and A. Krenzinger, “Degradation analysis of a photovoltaic generator after operating for 15 years in southern Brazil,” Solar Energy, vol. 196, pp. 196–206, 2020.

[18] I. A. Tsanakas, F. Mezzasalma, M. Babics, A. Mignonac, H. Colin, R. Couderc, L. Sicot, P. Marechal, G. Capron, and J. Aimé, “Fifteen years under the sun: Real-field degradation analysis of veteran PV modules,” in Proc. 42nd Eur. Photovolt. Solar Energy Conf. and Exhibition, 2025
[19] R. Roodt, E. vas Dyk, J. Crozier McCleland, M. Vumbugwa, F. J. Vorster, O. Stroyuk, and C. Buerhop-Lutz, “Degradation and defect characterisation of field-deployed silicon PV modules,” in Proc. 42nd Eur. Photovolt. Solar Energy Conf. and Exhibition, 2025.
[20] S. Pingel, M. Köntges, and others, “Degradation in PV power plants: Theory and practice,” in Proc. 35th Eur. Photovolt. Solar Energy Conf. and Exhibition (PVSEC), 2018.
[21] K. Chen, J. Zuo, and R. Chang, “Compendium of degradation rates of global photovoltaic (PV) technology: Insights from technology, climate and geography,” Solar Energy Mater. Solar Cells, vol. 293, p. 113839, 2025.
[22] B. Bora, O. S. Sastry, R. Kumar, R. Dubey, S. Chattopadhyay, J. Vasi, and B. Prasad, “Failure mode analysis of PV modules in different climatic conditions,” IEEE J. Photovolt., vol. 11, no. 2, pp. 453–460, 2020.
[23] H. Al Mahdi, P. G. Leahy, M. Alghoul, and A. P. Morrison, “A review of photovoltaic module failure and degradation mechanisms: Causes and detection techniques,” Solar, vol. 4, no. 1, pp. 43–82, Jan. 2024.
[24] IEA PVPS Task 13, "Photovoltaic Failure Fact Sheets (PVFS)," IEA-PVPS T13-30:2025, 2025. [Online]. Available: https://pvpmc.sandia.gov/workshops-and-pubs/iea-pvps-task-13-reports/
[25] M. Libra, D. Mrázek, I. Tyukhov, L. Severová, V. Poulek, J. Mach, and J. Sedláček, “Reduced real lifetime of PV panels–Economic consequences,” Solar Energy, vol. 259, pp. 229–234, 2023.
[26] R. Ciric, E. L. Håkedal, O. T. Pedersen, and K. O. Dørum, “Reliability and Electrical Safe-ty of Grid-Connected Household PV Systems: Data-Driven Risk Analysis and Insights,” Smart Energy, vol. 100182, 2025.
[27] P. Nain and A. Kumar, “Understanding manufacturers’ and consumers’ perspectives towards end-of-life solar photovoltaic waste management and recycling,” Environment, Development and Sustainability, vol. 25, no. 3, pp. 2264–2284, 2023.
[28] E. Meza, Reusing PV Modules Poses Opportunities and Challenges, PV Magazine International, Mar. 8, 2021. [Online]. Available: https://www.pv-magazine.com/2021/03/08/reusing-pv-modules-pose-opportunities-and-challenges/
[29] T. Charlemont, Revamping and Repowering, Intersolar News Interview, [Online]. Available: https://www.intersolar.de/news/interview-tomas-charlemont-revamping-and-repowering
[30] M. Späth, S. Wieclawska, P. Sommeling, and F. Lenzmann, Balancing Costs and Revenues for Recycling End-of-Life PV Panels in the Netherlands, TNO Report 2022 R10860, 2022.
[31] P. Nain and A. Anctil, “End-of-life solar photovoltaic waste management: A comparison as per European Union and United States regulatory approaches,” Resources, Conservation & Recycling Advances, vol. 21, p. 200212, 2024.
[32] K. Komoto, M. Held, C. Agraffeil, C. Alonso-Garcia, A. Danelli, J. S. Lee, and P. Sinha, Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries, Report IEA-PVPS T12-24, 2022.
[33] Kiwa PVEL and Kiwa PI Berlin, Raising the Bar: Defining Acceptable Quality Levels for PV Modules, Kiwa, 2024. [Online]. Available: https://www.kiwa.com/globalassets/usa/pvel/resources/raising-the-bar-kiwa-solar-2024.pdf.
[34] M. Köntges, S. Kurtz, C. Packard, U. Jahn, K. Berger, H. de Moel, et al., “Review of failures of photovoltaic modules,” IEA PVPS Task 13 Report T13-01:2014, Jan. 2014.
[35] STS, “STS speaks at PV ModuleTech USA 2025: Addressing quality risks in emerging PV module manufacturing markets,” STS-Certified, 2025.
[36] S. Lust, S. Kuntamukkula, S. Friedrichs, and L. Podlowski, “Topcon Solar Modules: UV Degradation in Lab and Field Conditions,” in PV-Symposium Proceedings, vol. 2, Aug. 2025.
[37] Kiwa PVEL, Cracks and Outdoor Aging, Oct. 2025. [Online]. Available: https://www.kiwa.com/globalassets/usa/pvel/resources/2025_10_07-kiwa-pvel---t.-karin-cracks-and-outdoor-aging.pdf

[38] M. Bartholomäus, N. Riedel-Lyngskær, L. Morino, M. Dhimish, P. Stefanidis, I. Razanakoto, and S. V. Spataru, “Field degradation of bifacial photovoltaic modules in northern Europe,” Solar Energy, vol. 300, p. 113786, 2025.
[39] M. Theristis, J. S. Stein, C. Deline, D. Jordan, C. Robinson, W. Sekulic, and B. H. King, “Onymous early-life performance degradation analysis of recent photovoltaic module technologies,” Prog. Photovolt: Res. Appl., vol. 31, no. 2, pp. 149–160, 2023.
[40] E. Tarigan, “Identification of early operational defects in photovoltaic modules: A case study of a 24.9 MWp solar PV system in Sumatra, Indonesia,” Unconventional Resources, vol. 6, p. 100156, 2025.
[41] M. Kivambe, A. Abdallah, B. Figgis, M. Abdelrahim, M. Elgaili, D. Pillai, and B. Aissa, “Comprehensive assessment of performance and reliability of PERC, TOPCon and SHJ modules in desert climates,” Solar Energy, vol. 295, p. 113555, 2025.
[42] C. Molto, et al., “Review of Potential-Induced Degradation in Bifacial Photovoltaic Modules,” Energy Technol., vol. 11, no. 4, Apr. 2023, doi: 10.1002/ente.202200943.
[43] Intertek CEA, Cracking Cell Defect Detection. [Online]. Available: https://www.intertekcea.com/cea-blog/cracking-cell-defect-detection
[44] M. Bdour, Z. Dalala, M. Al-Addous, A. Radaideh, and A. Al-Sadi, “A comprehensive evaluation on types of microcracks and possible effects on power degradation in photovoltaic solar panels,” Sustainability, vol. 12, no. 16, p. 6416, 2020.
[45] RETC and VDE, PV Module Index Report 2023.
[46] RETC, PV Module Index Report 2024: RE+ Edition.
[47] RETC, PV Module Index Report 2025: September Edition.
[48] PV Tech, Assessing the Risk of UV Stress on High-Efficiency Solar Technologies. [Online]. Available: https://www.pv-tech.org/assessing-the-risk-of-uv-stress-on-high-efficiency-solar-technologies/
[49] E. A. Gaulding, E. C. Palmiotti, J. F. Karas, J. S. Mangum, S. W. Johnston, J. B. Gallon, and M. G. Deceglie, “UV+ damp heat induced power losses in fielded utility N-type Si PV modules,” Prog. Photovolt: Res. Appl., vol. 33, no. 11, pp. 1236–1246, 2025.
[50] F. T. Thome, P. Meßmer, S. Mack, E. Schnabel, F. Schindler, W. Kwapil, and M. C. Schubert, “UV-induced degradation of industrial PERC, TOPCon, and HJT solar cells: The next big reliability challenge?,” Solar RRL, vol. 8, no. 23, p. 2400628, 2024.
[51] PVEL, Potential-Induced Degradation (PID) Overview. [Online]. Available: https://scorecard.pvel.com/pid/
[52] P. Hacke, S. Spataru, B. Habersberger, and Y. Chen, “Field-representative evaluation of PID-polarization in TOPCon PV modules by accelerated stress testing,” Prog. Photovolt: Res. Appl., vol. 32, no. 5, pp. 346–355, 2024.
[53] J. Huang, H. Li, Y. Sun, H. Wang, and H. Yang, “Investigation on potential-induced degradation in a 50 MWp crystalline silicon photovoltaic power plant,” Int. J. Photoenergy, vol. 2018, no. 1, p. 3286124, 2018.
[54]Kiwa PVEL, 2025 ModuleTech – Kiwa PVEL Scorecard Insights. Kiwa, 2025.
[55] J.-N. Jaubert and T. Erion-Lorico, “Outside the boxplot: Exploring Kiwa PVEL’s PQP outliers,” PV Tech, May 28, 2024. [Online]. Available: https://www.pv-tech.org/outside-the-boxplot-exploring-kiwa-pvels-pqp-outliers/
[56] S. K. Chunduri and M. Schmela, Market Survey: Backsheets & Encapsulation 2024–2025, TaiyangNews, 2025. [Online]. Available: https://images.assettype.com/taiyangnews/2025-03 19/oz2uamdo/TaiyangNews_Backsheets_2025_V14.pdf
[57] T. J. Silverman, E. C. Palmiotti, M. Springer, N. Bosco, M. Deceglie, I. Repins, and A. Gaulding, Tough Break: Many Factors Make Glass Breakage More Likely, NREL/TP-5K00-91695, National Renewable Energy Laboratory, Golden, CO, USA, 2024.
[58] T. Weber, M. Heiser, A. Abu Sayed, R. Joziak, E. Tellez Rodriguez, N. Pongthanacharoenkul, S. Rindert, B. Lippke, C. Wong, S. Xuereb, M. Nezhad, D. Cowan, M. Lu, C. Buerhop-Lutz, and I. M. Peters, “Recent findings on glass-breakage issues: From factory production oversight, on-

site inspection and laboratory testing results," in Proc. 42nd Eur. Photovolt. Solar Energy Conf. and Exhibition, 2025.

[59] T. Erion-Lorico, Should We Be Positive About N-Type? A 2024 PV Module Reliability Scorecard Preview, Kiwa PVEL, 2024.

[60] PVEL, Mechanical Stress Sequence Overview. [Online]. Available: https://2023modulescorecard.pvel.com/mechanical-stress-sequence/

[61] D. Devir, Breaking Point: Understanding and Preventing PV Module Glass Fracture, PV Tech, 2025.

[62] M. Chang, C. Chen, C. H. Hsueh, W. J. Hsieh, E. Yen, K. L. Ho, and H. Chen, "The reliability investigation of PV junction box based on 1GW worldwide field database," in Proc. IEEE 42nd Photovoltaic Specialist Conf. (PVSC), pp. 1–4, Jun. 2015.

[63] PVEL, Failures Overview. [Online]. Available: https://2023modulescorecard.pvel.com/failures/

[64] E. Tarigan, "Identification of early operational defects in photovoltaic modules: A case study of a 24.9 MWp solar PV system in Sumatra, Indonesia," Unconventional Resources, vol. 6, p. 100156, 2025.

[65] O. Bamisile, C. Acen, D. Cai, Q. Huang, and I. Staffell, "The environmental factors affecting solar photovoltaic output," Renewable and Sustainable Energy Reviews, vol. 208, p. 115073, 2025.

[66] M. Bošnjaković, M. Stojkov, M. Katinić, and I. Lacković, "Effects of extreme weather conditions on PV systems," Sustainability, vol. 15, no. 22, p. 16044, 2023.

[67] S. Poddar, F. Rougieux, J. P. Evans, M. Kay, A. A. Prasad, and S. P. Bremner, "Accelerated degradation of photovoltaic modules under a future warmer climate," Prog. Photovoltaics Res. Appl., vol. 32, no. 7, pp. 456–467, 2024.

[68] E. Foley, "UNSW research finds high temperatures increase module degradation," pv magazine Australia, Feb. 20, 2024. [Online]. Available: https://www.pv-magazine-australia.com/2024/02/20/unsw-research-finds-high-temperatures-increase-module-degradation/.

[69] S. Johnston, D. B. Sulas-Kern, and D. Jordan, "Photovoltaic module imaging for hail damage assessment with multi-year follow up," in *Proc. 48th IEEE Photovoltaic Specialists Conf. (PVSC)*, Fort Lauderdale, FL, USA, Jun. 2021, pp. 763–766, doi:10.1109/PVSC43889.2021.9518491.

[70] R. Kennedy, "Hail risk remains top issue faced by solar projects," pv magazine, June 11, 2025. [Online]. Available: https://www.pv-magazine.com/2025/06/11/hail-risk-remains-top-issue-faced-by-solar-projects/

[71] T. Teule, M. Appeldoorn, P. Bosma, L. Sprenger, E. Koks, and H. de Moel, "The vulnerability of solar panels to hail," Vrije Universiteit Amsterdam, Amsterdam, Netherlands, 2019.

Energy & Materials Transition

Westerduinweg 3
1755 LE Petten
www.tno.nl