sustainability

MDPI

Article

Rapid Five-Year Repowering of Photovoltaic Power Plants in Demanding Climates: Effective Clean Recycling and Disassemblable PDMS Gel Encapsulation to Reduce the Environmental Impact

Vladislav Poulek [1,*] and Martin Kozelka [2]

[1] Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague, Czech Republic
[2] Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague, Czech Republic
* Correspondence: poulek@solar-solar.com

Abstract

Photovoltaic (PV) plants are typically assessed using ~25-year financial horizons and 25–30-year module performance warranties. However, experience from demanding climates shows that actual lifetimes can be shorter and that dry-condition insulation tests may underestimate risks under wet operation. In such cases, repowering after roughly five years can restore energy yield and reduce operational faults, but it also creates repeated waves of waste and increases manufacturing demand. This study synthesizes evidence on moisture-induced insulation loss, backsheet degradation, and delamination-driven failure escalation and complements it with a transparent 30-year scenario comparing module replacement every 5, 10, and 30 years. The findings suggest that humidity-dependent ground-impedance deterioration, frequent inverter trips, delayed morning start-up, and shutdown risks can emerge within about five years at challenging sites, while dry testing may fail to capture these issues. In a severe scenario, five-year repowering requires six full module sets over 30 years, significantly increasing waste volumes and pressure on manufacturing and recycling systems. Therefore, PV sustainability assessments should reflect the effective repowering interval rather than nominal warranties. Promising solutions include repowering-ready, disassemblable module designs, such as those using soft PDMS gel encapsulation.

Keywords: photovoltaics; repowering; revamping; reliability; insulation resistance; wet leakage; dew; delamination; polydimethylsiloxane (PDMS); circular economy; PV waste

Check for updates

Received: 5 March 2026
Revised: 1 April 2026
Accepted: 2 April 2026
Published: 7 April 2026

1. Introduction

PVs are widely expected to possess a ~30-year module service life; however, a subset of plants in demanding climates need to be repowered after ~5 years [1–6]. When repeated inverter trips, delayed morning startups, and escalating downtime become routine, early replacement becomes the pragmatic asset management choice [1–6]. In parallel, ongoing improvements in module efficiency and declining costs reinforce the economic incentive for earlier replacements, especially when the area and grid connection are fixed constraints [3–5].

With respect to sustainability, the consequence is mechanical: if repowering occurs every 5 years, then within a 30-year planning horizon, six complete module sets are deployed and decommissioned [3–6]. This creates increased waste and manufacturing demands. In other words, the sustainability outcome is governed by the repowering interval and not by the nominal service life expectation printed on a datasheet.

This study is based on a practical premise: repowering after ~5 years will occur in demanding climates (for at least a nontrivial segment of the fleet) due to a combination of reliability constraints and technology upgrading [1–6]. Field studies in harsh deployments repeatedly report accelerated degradation and defect accumulation within the first decade, supporting the plausibility of shortened effective lifetimes at demanding sites [7–11].

The goal is therefore to clarify why early repowering occurs, why wet condition insulation is central, and how the environmental impacts can be reduced when repowering becomes frequent. The central technical message is that field screening is typically performed under dry conditions for speed, whereas wet operation is routine and can reveal latent failures; the central sustainability message is that frequent repowering requires end-of-life routes that are both highly efficient and low emission, preferably enabled by repowering ready module construction.

Independent field evidence reinforces the five-year severe case premise. In a 5 MWp PV power station, inverter shut-downs were observed at least twice as often for fluorinated-coating-based backsheets as for polyamide-based backsheets, and a subsequent dynamics study found an onset of ground-impedance degradation at 4.9 years for the former class. In parallel, field data from a desert-maritime PV plant confirmed that major degradation trends were assessed within the first five years of operation in a demanding climate [12–14].

1.1. Repowering as an Operational Reality—Not an Exception

The revamping and repowering of solar PV plants have been analyzed as technical and economic decisions with multiple alternatives, which are strongly dependent on the site constraints and assumptions [1]. Module replacement has also been discussed as a mechanism that can accelerate technological upgrading and market entry by allowing a mature BOS and grid connection to host higher performance modules [2]. At the fleet scale, such decisions matter more as global deployment expands, and the installed base ages [3]. Technological reporting confirms the continuing efficiency improvements and increases in module power [4], whereas cost assessments reveal that PVs are a competitive generation option in many regions [5]. These trends make repowering attractive even when the existing plant has not yet reached its "end of life" in the conventional sense.

In demanding climates, the economic incentive is frequently reinforced by a reliability incentive: repeated protective trips and inverter unavailability translate into a high opportunity cost. When that cost accumulates early on, repowering becomes the simplest method to restore stable operations. It is therefore realistic to treat 5-year repowering as an operational practice that must be addressed in sustainability planning rather than as a hypothetical corner case [1–6]. This positions repowering as a realistic asset-management option; the next step is to summarize why the effective service life can be shortened in demanding climates.

This five-year framing is further supported by recent field studies linking backsheet family, humidity, ground-impedance deterioration, and inverter availability in utility-scale PV plants. In particular, FC-based backsheet systems were shown to enter the critical low-ground-impedance regime substantially earlier than PA-based systems, with the onset of degradation determined at 4.9 years of operation in a dynamic analysis [12,13]. Importantly, the ~5-year interval used later in scenario S0 is not presented as a representative lifetime for the global PV fleet. It is a severe-case scenario for demanding sites where reliability pressures and upgrading incentives can compress the effective replacement interval.

1.2. Short Effective Service Life in Demanding Climates

Reduced real lifetimes have been discussed explicitly together with their economic consequences, demonstrating how a shorter service life changes the project economics and replacement strategies [6]. The literature on harsh deployments reports that degradation and reliability challenges can be accelerated under combined stressors, such as heat, humidity, UV, dust, and salt. Long-term performance and reliability analyses under tropical conditions report notable reliability challenges [7]. The field exposure of crystalline silicon modules has demonstrated a performance evolution under real outdoor conditions that can diverge from simplified planning assumptions [8]. In tropical environments, degradation evaluations after only a few years reveal that early degradation and defect accumulation can significantly depend on the climate and construction factors [9]. Similar conclusions have been reached in studies of harsh desert and arid deployments, where climatic stressors affect module behavior and performance [10]; an in situ evaluation under harsh Moroccan conditions revealed the early degradation of various technologies [11].

These studies do not imply that all PV plants will need to repower after five years. However, in demanding climates, the effective service life can be shortened enough so that early replacement becomes practical; in those cases, the sustainability analysis must reflect the real replacement interval rather than a nominal expectation. Given this background, we next focus on wet condition insulation behavior as an operational trigger that can translate module aging into inverter trips and early repowering pressure.

1.3. Wet Condition Insulation Is Routinely Relevant and Commonly Under-Screened

The insulation resistance (ground impedance, R_{isol}) between PV DC circuits and accessible conductive parts/grounds is a key safety and reliability metric: a low Risol value can trigger inverter protection and indicate potentially hazardous leakage, and wet operations are routine because dew, fog, and rain films commonly form (especially around sunrise), while colder modules can also increase open-circuit voltages [15–17]. fThis can misrepresent the risk because moisture activates surface/edge leakage pathways and because degradation at polymeric interfaces (frame edges, backsheets, and junction boxes) can create wet-activated conduction routes that differ across backsheet constructions and evolve over time [12,13,18–20], with plant-scale impacts documented under severe moisture exposure situations, such as flooding [21]. High-voltage stress mechanisms (e.g., PID) may further interact with the string voltage and leakage conditions, particularly in harsh environments [22].

Plant-scale evidence indicates that insulation- and backsheet-related issues can range from module defects to system-level alarms and inverter shutdowns. A multi-MW PV power station case study reported backsheet-driven field issues consistent with increasing insulation-related events [12]. Subsequent work quantified “dynamics of backsheet-driven insulation issues”, highlighting that the observed behavior depends on backsheet material families and aging pathways [13,18–20]. Extreme moisture exposure can further degrade insulation margins, as shown by a flooded PV power plant case study in Thailand [21].

Recent IEC wet testing of N = 37 field-aged crystalline silicon modules demonstrated that dry-only measurements can strongly overestimate wet insulation and revealed a dry–pass/wet–fail population [23]. This population is operationally critical because it creates a latent trip risk during routine wet mornings: modules appear acceptable in dry screening but fail under wet conditions. The outcome categories at the conceptual level are summarized in Figure 1 on the basis of the published statistics. In addition, delamination-assisted water ingress has been shown to increase toward inverter switch-off and potential damage under high-string-voltage conditions [24]. This interpretation is consistent with independent field studies in which backsheet family, humidity, and the evolution of ground impedance were directly linked to inverter availability and early operational risk [12,13].

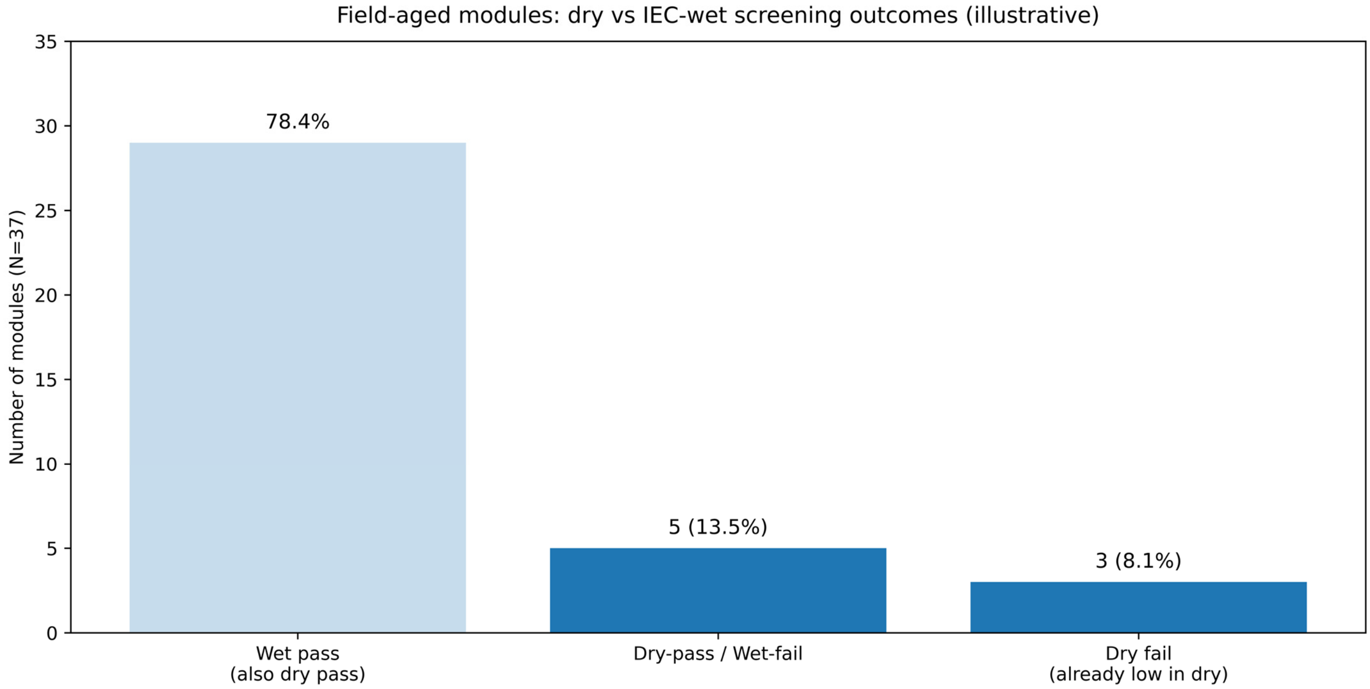

Figure 1. Field-aged modules: dry versus IEC wet screening outcomes (illustrative, based on the published statistics in [23]).

1.4. Sunrise Window: Wet Surfaces Can Coincide with High DC Voltage

The co-occurrence of wet surfaces and a high string voltage is most relevant around sunrise. Moisture film can persist into the morning hours, while the module temperature remains low and increases the Voc. In practice, this explains why insulation-related events often cluster around sunrise and why inverters can remain off until the Risol value rises above the protection thresholds. Figure 2 provides a stylized proxy for this combined window and is included for clarity (not as a site-specific predictive model).

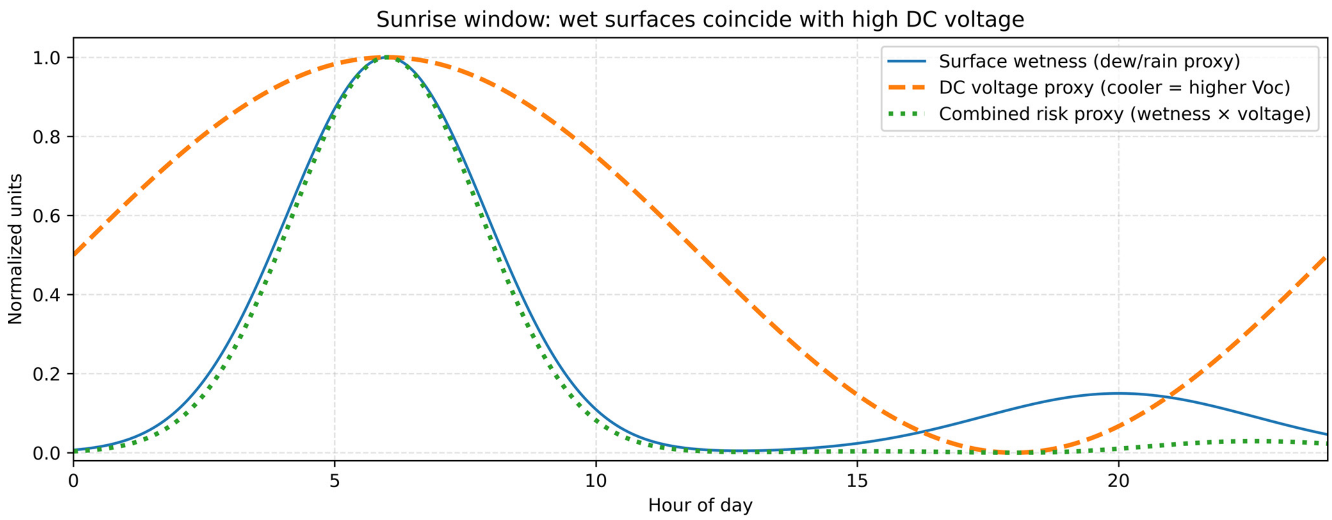

Figure 2. Sunrise window: wet surfaces coincide with high DC voltage (stylized proxy, supported by [15–17]).

1.5. Failure Escalation: From Delamination to Inverter-Level Impacts

Wet leakage issues do not only cause nuisance trips. A documented field pathway links edge delamination to water penetration and the formation of discharge channels between the string conductors and grounded frames, leading to an inverter switch-off and, after repeated discharges, potentially inverter downtime and damage [24]. Because one inverter affects multiple strings, a limited number of defective modules can propagate into inverter-level energy losses and increase the operational risk. This "multiplication effect" alters repowering from an economic optimization method to a risk control decision. The escalation chain, from edge delamination and water ingress to discharge channels, Risol reduction, inverter events, and downtime/damage, is summarized in Figure 3.

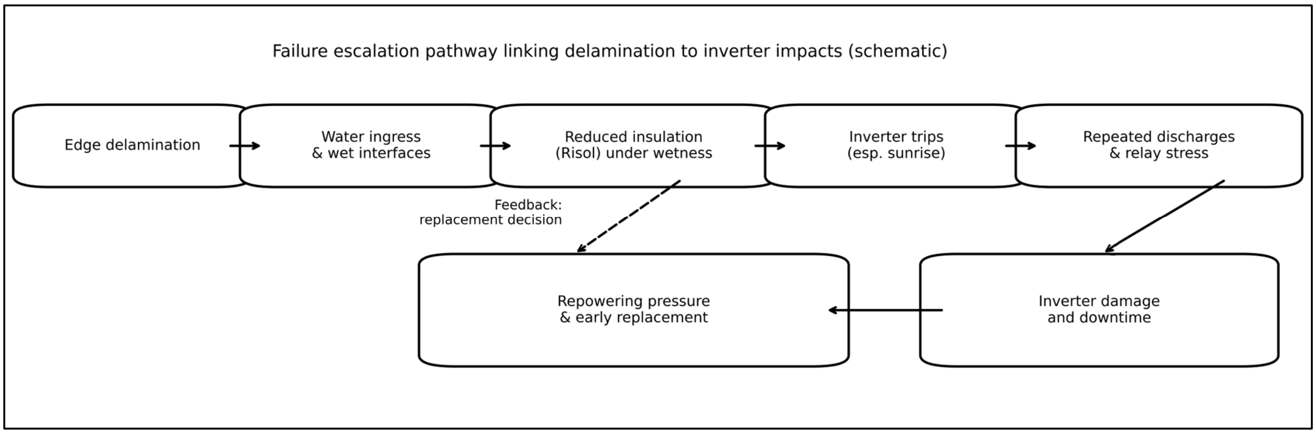

Figure 3. Failure escalation pathway linking delamination to inverter impacts (schematic, based on [24]).

1.6. Repowering Pressure and Technology-Driven Efficiency Improvements

Repowering is not driven by reliability alone. Ongoing improvements in module efficiency and power density strengthen the replacement incentive, as the same area and BOS can deliver a higher output after repowering. An illustrative long-term efficiency trend that is consistent with the published technology reporting is provided in Figure 4 [4]. When efficiency gains coincide with reliability constraints (wet trips, escalating downtime), repowering becomes both technically and economically rational.

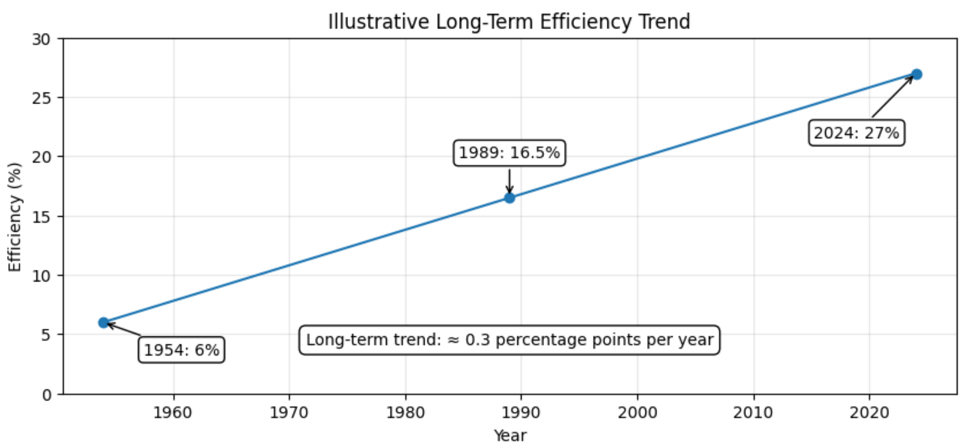

Figure 4. Illustrative long-term efficiency trend (absolute percentage points, consistent with [4]).

1.7. Objectives and Research Logic

While repowering/revamping options [1,2], shortened effective lifetimes [6–11], wet condition insulation risk and standards [15–17,22,25], and PV end-of-life management [26–29] have each been studied, this work links them into one operationally grounded sustainability problem: (i) how wet condition insulation failures and delamination-driven escalation can make a rational operator decision within ~5 years [12,13,23,24], (ii) how such short repowering intervals mechanically amplify PV waste and manufacturing demand ("surges"), and (iii) how disassemblable PV panel/module design using soft PDMS gel encapsulation can reduce the environmental impacts under repeated replacements by enabling room-temperature delamination and high direct reuse fractions [26]. In this context, Table 1 is intended only as an illustrative comparison of process burdens in conventional laminated-module separation; it is not a full life-cycle assessment.

Table 1. Illustrative comparison of process burdens in conventional laminated c-Si PV module separation (not a full life-cycle assessment).

Item	Conventional Laminated Glass/TPT PV Panel, Weight ~22 kg
Backsheet [~1 kg]	Polymer/TPT separation often requires thermal and/or chemical treatment;
Encapsulant [3 kg]	EVA/POE separation is often burden-dominant; direct emissions/residues
Front glass sheet [15 kg]	Recoverable fraction; secondary remelting impacts are not included here
Polymer J-box [~0.5 kg]	Recoverable fraction; secondary remelting impacts are not included here
Aluminum frame [2 kg]	Recoverable fraction; secondary remelting impacts are not included here
c-Si solar cells [0.8 kg]	Recoverable/refinable fraction; secondary processing impacts are not included here
Direct Reuse	Very limited in conventional irreversible lamination
Direct Hazardous Emissions	Substantial in polymer-separation steps; 15% weight; route-dependent
Recycling Efficiency	~15 ÷ 90% (process- and design-dependent)

Note. Table 1 is intended only to illustrate why polymer-containing laminate-separation steps dominate the practical recyclability challenge in conventional modules. It does not provide a full mass balance or a complete LCA. The comparison excludes upstream energy supply, transport, capital equipment, secondary remelting/refining burdens, and site-specific emission controls. Accordingly, the direct residues/emissions associated with conventional polymer separation should be understood as route-dependent rather than universal values.

This study adopts a practical stance: repowering after ~5 years will occur in a subset of plants in demanding climates despite the ~30-year expectation. The question is how to reduce the environmental impact when this becomes the operating reality.

Therefore, our objectives are as follows:

1. To frame wet condition insulation behavior as a routinely relevant operational driver and to document why dry-only screening can overlook wet failures [23,25].
2. To summarize a plausible failure escalation pathway linking module defects to inverter-level impacts [24].
3. To quantify, using a transparent 30-year scenario model, how a 5-year repowering practice changes the waste timing ("surges") module throughput multipliers and manufacturing diversion.
4. To argue, on technical and sustainability grounds, that the construction of repowering ready modules that enable clean disassembly and high direct reuse—specifically soft PDMS gel encapsulation—reduces the environmental burden of inevitable repowering processes [26].
5. To place the above in the context of EoL management and embodied emission variability [26–28].

2. Materials and Methods

The methodological workflow is summarized in Figure 5 and consists of four steps: (i) evidence synthesis on wet condition insulation and delamination-driven escalation,

(ii) definition of repowering scenarios over a 30-year horizon, (iii) translation of scenarios into waste timing using a Weibull-based baseline representation and an exogenous repowering trigger, and (iv) reporting of transparent indicators (waste "surges", throughput multiplier, and manufacturing diversion) with a compact sensitivity analysis.

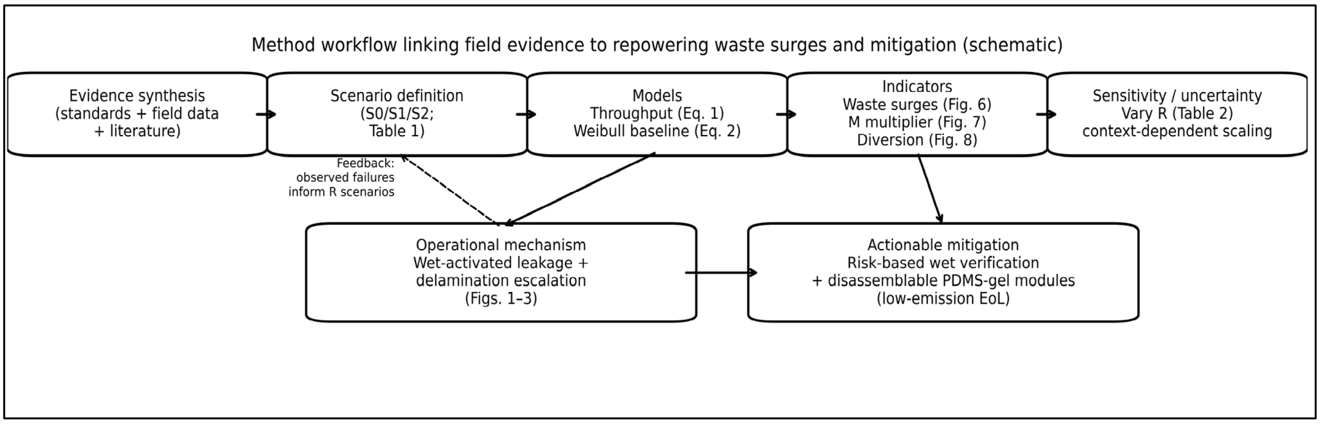

Figure 5. Method workflow and inputs/outputs (evidence → scenarios → models → indicators and sensitivity).

2.1. Evidence Base

In this study, we synthesize the published evidence on the following: wet leakage standards and field-aged wet insulation [23,25]; dew/rain moisture relevance [15]; insulation safety and modeling [16,17]; backsheet-driven insulation issues [12,13,18–20]; flooding impacts [21]; PID under high voltages [22]; delamination-driven inverter impacts [24]; and demountable encapsulation and recycling using soft PDMS/polysiloxane gels [26]. The sustainability discussions are grounded in the EoL management literature [27] and in the established analysis of greenhouse gas emissions associated with PV electricity [28]. The evidence base combines (a) standards (IEC), (b) peer-reviewed field and laboratory studies, and (c) PV end-of-life synthesis reports used as baseline references for PV waste modeling [29,30]. We explicitly prioritized recent field evidence (2021–2026) where available, including.

Recent field evidence (2021–2026), where available, was prioritized for backsheet-driven insulation loss, latent field defects, and demanding-climate performance degradation because these studies most directly inform the practical severe-case scenario framing used in S0 [12–14,23,31,32].

2.2. Functional Unit and System Boundary

The functional unit is 1 kW of installed module capacity, delivering service over a 30-year planning horizon (the commonly used expectation). The scenario model focuses on modules (dominant repeated mass flow under frequent repowering). The BOS is assumed to be largely reusable during repowering; BOS impacts are addressed qualitatively via limitations. The purpose of this study is not to deliver a full LCA with site-specific inventories; instead, we provide a transparent scenario model that isolates the first-order scaling effect of the repowering interval on (i) PV panel/module waste timing and (ii) repeated manufacturing/EoL processing demand. Accordingly, the comparison of recycling routes in Table 1 should be interpreted as an illustrative process comparison rather than as a complete cradle-to-grave emissions inventory.

2.3. Scenarios

We define three scenarios:

- S0 (rapid representation): Full module replacement every 5 years → six complete module sets over 30 years.
- S1 (sensitivity): Full module replacement every 10 years → three complete module sets over 30 years.
- S2 (baseline expectation): No replacement within 30 years → one module set over 30 years.

The central comparison is S0 versus S2, as this captures the mismatch between the ~30-year expectation and the practical ~5-year repowering behavior.

For clarity and reproducibility, the scenario definitions and replacement event years are summarized in Table 2.

Table 2. Scenario definition and throughput multiplier M (for $H = 30$ years).

Scenario	Repowering Interval R (Years)	Module Sets over 30 Years M (=H/R)	Repowering Events (Years)	Final Decommissioning (Year)
S0	5	6	5, 10, 15, 20, 25	30
S1	10	3	10, 20	30
S2	30	1	–	30

The 5-year interval in S0 is an explicit scenario assumption motivated by the published evidence that (i) some plants experience repowering pressure in approximately 5 years in severe cases and 5–10 years more broadly under demanding conditions [6,12–14,23,30–32], and (ii) wet condition insulation failures and delamination-driven escalation can plausibly translate the module defects into inverter-level downtime and replacement pressure [23,24]. This manuscript does not claim that all PV plants need to repower after 5 years; S0 represents a demanding climate subset.

2.4. Indicators and Models

Three indicators follow directly from the scenarios:

1. Waste timing: Replacement events create discrete waste "surges" over time.
2. Module throughput multiplier: The number of module sets installed per 30 years (mechanical multiplier for manufacturing and EoL flows).
3. Stylized manufacturing diversion: The replacement demand consumes the factory output, which could otherwise supply new deployments.

These are first-order indicators, and they were deliberately chosen: they quantify the scale and timing without requiring detailed plant-specific optimization.

2.4.1. Throughput Multiplier (Equation (1)) and Scenario Sensitivity (Table 3)

We define the module throughput multiplier M as the number of complete module sets required over the planning horizon H:

$$M = \frac{H}{R} \quad (1)$$

where H = 30 years, and R is the repowering interval (years). The scenario values of R and M are reported in Table 2. A compact sensitivity analysis of M versus R is provided in Table 3 to avoid the deterministic interpretation of "5 years" and to show how the results scale for alternative replacement intervals.

Table 3. Sensitivity of the throughput multiplier M to the repowering interval R (for $H = 30$ years).

R (years)	5	7.5	10	15	30
M (=H/R)	6.0	4.0	3.0	2.0	1.0

2.4.2. Waste-Timing Baseline Using Weibull Cumulative Loss (Equation (2)) and the Exogenous Repowering Trigger

To visualize the discontinuity between a nominal long-life loss progression and a rapid repowering practice (Results, Section 3.4), we reproduce the Weibull cumulative probability-of-loss representation used in the IRENA/IEA-PVPS PV panel waste model as a baseline and then overlay the repowering trigger adopted in S0 [29].

The Weibull cumulative distribution function is as follows:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{T}\right)^{\alpha}\right] \quad (2)$$

where t is time (years), T is a scale parameter (years), and α is the shape factor as parameterized in the IRENA/IEA-PVPS model [29].

Importantly, the IRENA/IEA-PVPS model does not explicitly include repowering; therefore, in this study, repowering is introduced as an exogenous scenario rule: full replacement at $t = R$, $2R$, and $3R$ up to the horizon H (Table 2). The resulting waste timing is therefore a stepwise sequence of "surges" during repowering event years rather than a single end-horizon decommissioning wave (Results, Section 3.4; Figure 6b).

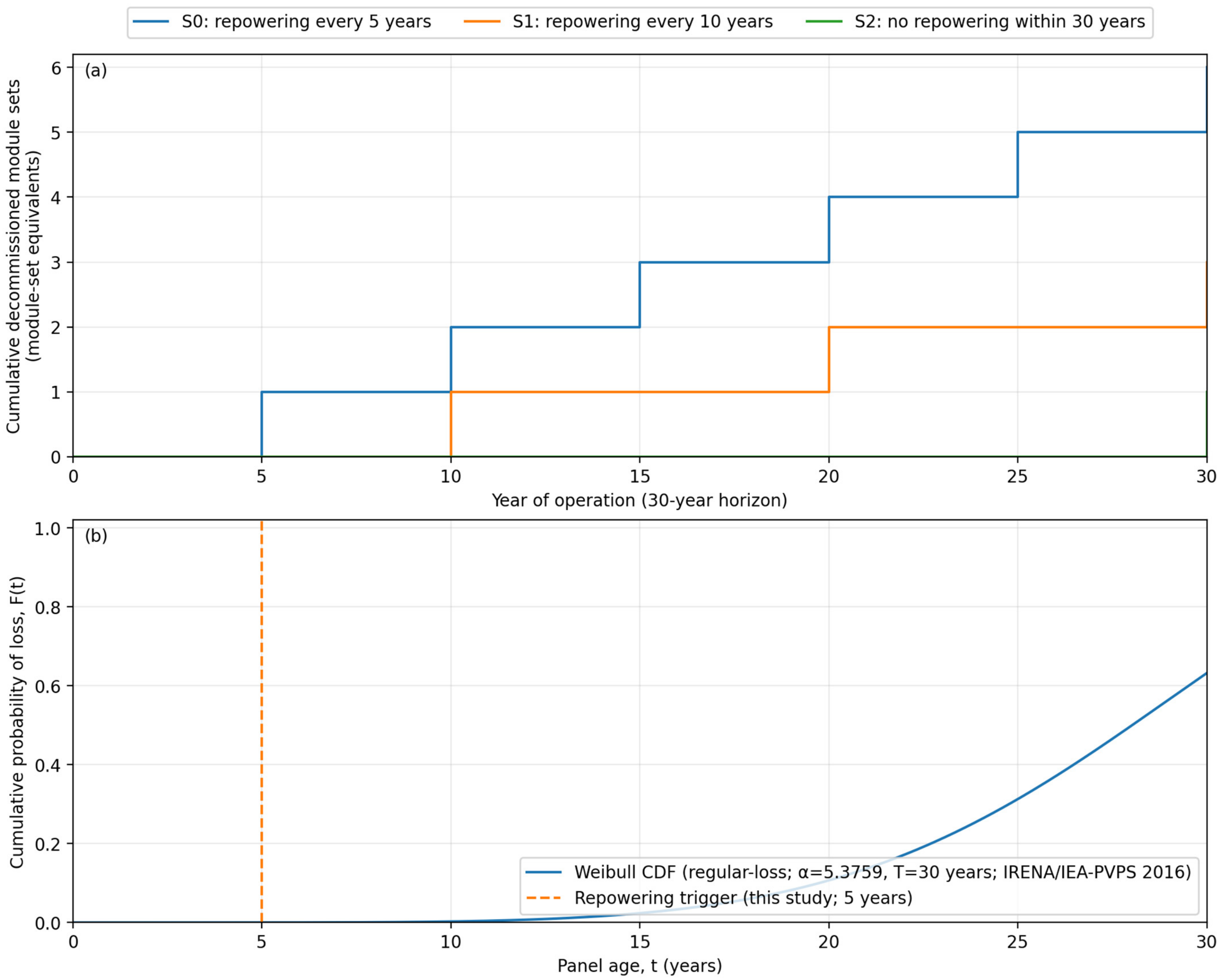

Figure 6. (**a**) Weibull-based reference curve with the repowering trigger used in S0 (5 years, dashed line). (**b**) Stylized cumulative waste over 30 years expressed in module-set equivalents, with step increases at replacement event years [29].

2.4.3. Uncertainty Framing

This is a scenario-based analysis and not a predictive model for a specific plant. Uncertainty is expressed primarily through sensitivity to the repowering interval R (Table 3). The main qualitative conclusion—that short repowering intervals mechanically multiply throughput and create repeated waste surges—does not depend on the exact Weibull parameter values because it is dominated by the replacement interval R through Equation (1). Additional uncertainties, such as BOS turnover, transport distance, and route-specific recycling burdens, are not parameterized here and are therefore discussed qualitatively in the limitations section.

3. Results

3.1. Wet Condition Operation Creates a Sunrise Risk Window

Moisture films (dew and rain) tend to peak around sunrise, while the string voltage can be high because the cell temperature is low (higher V_{oc}). This combination amplifies the probability that moisture-activated leakage pathways reduce R_{isol} and trigger inverter ground fault protection [15–17,23]. The key operational point is not only that wet conditions occur but also that they occur at a time when the voltage conditions are unfavorable for the insulation margins. The stylized proxy of this combined window is shown in Figure 2. This "sunrise window" provides the operational rationale for focusing on wet condition insulation behavior as a practical repowering trigger (see Section 2.1 and scenario logic in Section 2.3).

3.2. Dry-Only Screening Can Miss Wet Failures at Non-Trivial Rates

IEC-conformant wet leakage testing of field-aged modules reveals that dry measurements can systematically overestimate wet insulation and that a dry–pass/wet–fail population exists [23].

3.3. Delamination-Driven Escalation Increases Repowering Pressure

The delamination pathway provides a mechanism for escalation: edge delamination $\rightarrow$ water ingress $\rightarrow$ conductive wet interfaces $\rightarrow$ discharge channel formation to ground frames $\rightarrow$ inverter switch-off because of low R_{isol} $\rightarrow$ repeated discharges stressing protective components $\rightarrow$ downtime and potential damage [24]. This coupling creates a non-linear maintenance curve: early morning trips can evolve into high-cost inverter impacts, which shifts the operator's decision toward a replacement. This mechanism is summarized in Figure 3. This is the key pathway through which module-level degradation can scale into inverter-level downtime and contribute to early repowering decisions (Section 4.3).

3.4. Waste Timing: 5-Year Repowering Produces Repeated "Year 5 Surges"

To visualize the discontinuity between a nominal long-life loss progression and a rapid repowering practice, Figure 6a reproduces the Weibull cumulative probability of the loss curve used in the IRENA/IEA-PVPS PV panel waste model for the regular-loss scenario (Equation (2), with t in years and parameters T and α as in [29]) and overlays the 5-year repowering trigger $R = 5$ years adopted here for scenario S0 [29]. Importantly, the original IRENA/IEA-PVPS waste model explicitly excludes repowering; the 5-year interval is therefore introduced in this study as an exogenous scenario assumption (Section 2.3) to represent observed rapid repowering practices in demanding climates [6,12–14,23].

Applying this 5-year trigger yields replacement events at years 5, 10, 15, 20, and 25 plus final decommissioning at year 30 (Table 2). Under S2, the primary decommissioning event occurs at year 30. These events are translated into cumulative waste expressed in module set equivalents, i.e., the cumulative count of PV panel/module sets reaching the EoL over the 30-year horizon (Figure 6b). The result is mechanical: within a 30-year planning horizon, S0 requires six complete module sets, $M = 6$; Equation (1); Table 2) and therefore generates repeated waste, rather than a single late-horizon decommissioning wave. As shown in Table 3, the multiplier scales inversely with the repowering interval (Equation (1)); e.g., R = 10 years implies $M = 3$, and $R = 7.5$ years implies $M = 4$.

3.5. Module Throughput Multiplier Scales with a Repowering Interval

The number of module sets manufactured per 30-year service period is summarized in Figure 7. The multiplier is again mechanical: S0, S1, and S2 correspond to six (6×), three (3×), and one module set (1×). These values follow directly from the throughput multiplier definition (Equation (1)) and are listed explicitly in Table 2. This multiplier is the first-order driver of repeated manufacturing, transport, and EoL processing under short repowering cycles. Table 3 provides a compact scaling check showing how M changes with alternative repowering intervals R, preventing the deterministic interpretation of "5 years" as a universal outcome.

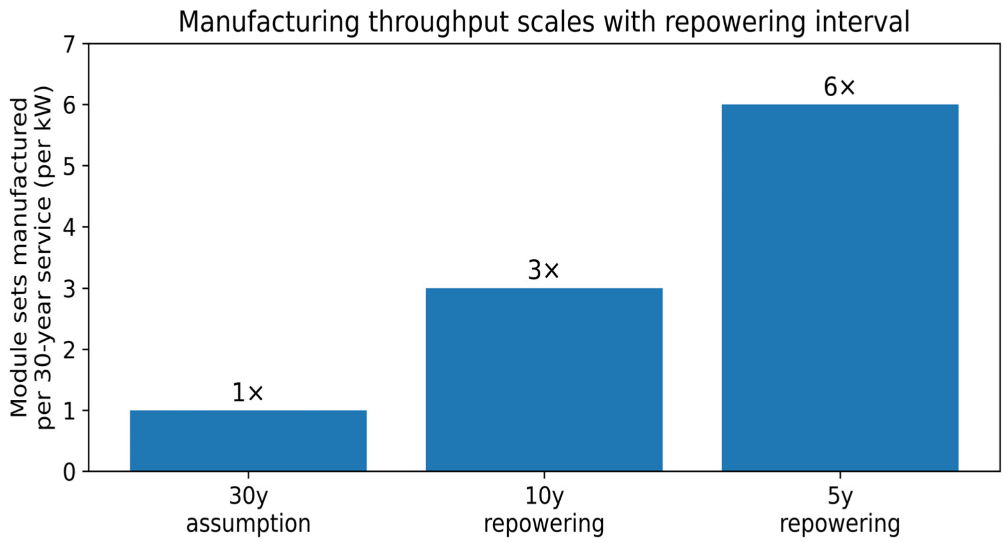

Figure 7. Manufacturing throughput scales with a repowering interval (module sets per 30-year service period).

3.6. Manufacturing Capacity Constraint: Replacement Demand Diverts Output from New Deployment

At the system level, the replacement demand competes with new deployment for manufacturing output. The stylized factory model in Figure 8 illustrates this effect: if a fixed manufacturing capacity supplies both growth and replacement, then short repowering intervals cause an earlier saturation of the "new fleet supplied" because the output is increasingly consumed by the replacement. This is an energy transition constraint when the replacement demand becomes substantial, as it reduces how much of the new net capacity can be added for a given manufacturing base.

A simple capacity interpretation follows directly from Equation (1): a single site repowered on a 5-year interval consumes $M = 6$ module sets over 30 years, i.e., five additional sets compared to the baseline ($M = 1$). Those five additional sets are manufacturing capacity that could otherwise deploy approximately five new sites of the same size (all else equal). This qualitative diversion effect is illustrated schematically in Figure 8.

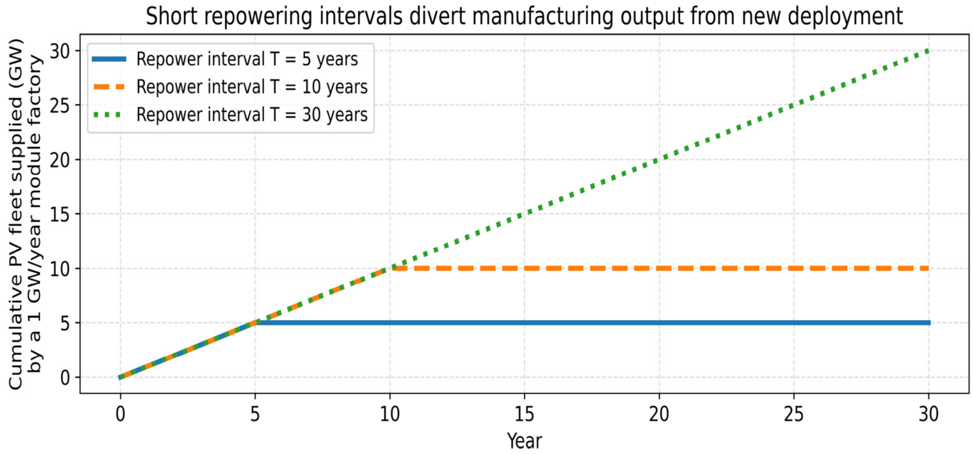

Figure 8. Short repowering intervals divert manufacturing output from new deployment (stylized illustration).

4. Discussion

4.1. The Core Discontinuity: 30-Year Expectation Versus 5-Year Practice

If a plant is planned and marketed with a ~30-year service life in mind but in practice is repowered after ~5 years, then a sustainability analysis based on the nominal expectation will understate both the waste and repeated manufacturing. The difference is not subtle: a 5-year repetition implies six module sets and six waste events per 30 years. This is a decisive multiplier, independent of the details of any LCA model.

The real question is therefore operational: why does a plant become repower prone after ~5 years, and how can the environmental impact be reduced when repowering becomes the practical option? The evidence reviewed here supports two technical drivers that are consistent with field observations: (i) wet condition insulation behavior that can be underestimated by dry screening and (ii) delamination-driven escalation that couples module defects to inverter availability [23,24]. Together with technology-upgrading pressures (efficiency gains) [4], these drivers make repowering after ~5 years an expected practice for a subset of demanding sites. Additionally, in sunny and hot climates with annual specific yields of up to approximately 1800 kWh/kW, the return on investment (ROI) can be shorter than five years [23].

Independent field evidence now strengthens this five-year framing by showing that humidity-related ground-impedance deterioration and inverter shut-down risk can emerge on approximately that timescale in real utility-scale plants [12,13].

4.2. Wet Condition Insulation Verification: A Practical Lever

The fact that IEC wet leakage testing is primarily used for type approval [25] but that field screening is usually dry creates a practical gap. Wet operation is routine, and field evidence demonstrates that dry-only screening can miss wet failures [23]. In demanding climates, particularly where sunrise trip patterns occur, wet condition insulation verification should be treated as a risk-based O&M tool.

The operational intent is simple: identify module/string populations likely to trip under routine wet mornings and prevent escalation. Practical triggers for wet condition verification include the following:

- Repeated sunrise trips and delayed morning start-ups;
- R_{isol} alarms correlated with dew/rain events;
- Visible edge/interface degradation;
- Module populations in which the backsheet family and aging history are present are associated with increased leakage susceptibility [12,13,18–20].

The supporting literature on backsheet-driven insulation issues [12,13,18–20], flooding [21], and high-voltage degradation mechanisms, such as PID [22], reinforces the idea that moisture and voltage stressors should be treated as central reliability variables in demanding climates.

4.3. Why Delamination Escalation Changes the Repowering Decision Threshold

The delamination pathway in [24] explains why repowering can become urgent. Once discharge channels and repeated discharges occur, the problem becomes an inverter availability and potential damage issue rather than a mild performance loss. The "multiplication effect" is practical. A limited number of defective modules can affect an inverter and therefore propagate into large energy losses and high O&M burdens. Under those conditions, full replacement becomes an economically rational risk control decision, even if sustainability outcomes worsen.

This is the link between technical reliability and sustainability. If we want to reduce the environmental impact of inevitable repowering, we must address both the triggering failure modes (wet insulation and delamination pathways) and the end-of-life processing of repeated surges. In the rapid-repowering scenario S0, these operational triggers translate into repeated module replacement events (Table 2), which in turn generate the stepwise waste surges shown in Figure 6 and the throughput multiplier M shown in Figure 7 (Equation (1)).

4.4. Repowering Ready Circular Module Construction: Why Soft PDMS Gels Matter

If repowering after ~5 years is the reality for a segment of the fleet, then the sustainability problem is not only "how to recycle more" but "how to repower without creating high-emission waste handling and low-value disposal".

Here, the circular design choice becomes central. Soft PDMS/polysiloxane gel lamination has been reported as an approach that enables room-temperature mechanical delamination, high recycling efficiency, and high direct reuse fractions, avoiding high-temperature burning and aggressive chemical etching [26]. In this framework, a large portion of the module mass can be recovered as reusable components rather than being downcycled or disposed, and the processing time can be shortened (rapid disassembly) [26]. Work on silicone-gel-laminated modules reported very low degradation rates over multi-decade observation periods and supported the general claim of high stability for gel-based encapsulation [33].

The published evidence supporting silicone/PDMS durability is broader than a single laboratory concept [26]. Ketola et al. reported very low degradation after 26 years of outdoor exposure and small UV-transparency loss for silicone-gel lamination relative to EVA [33]. Hara et al. showed that silicone-sheet encapsulants improved module durability against potential-induced degradation and damp–heat stress [34]. Lopez-Garcia et al. analyzed silicone-encapsulated PV modules after more than 30 years of outdoor exposure in a semi-tropical climate and found only very limited degradation of the silicone material [35]. A review further summarizes that silicones combine excellent chemical inertia, resistance to oxidation and heat, good UV transparency, and very low water uptake [36]. In the present manuscript, PDMS-based gel encapsulation is discussed as a promising repowering-ready option rather than as the only possible circular design route. The key point is the design logic itself—easier disassembly, higher reuse potential, and reduced burden during repeated replacement cycles—while any specific implementation would still require verification of durability, wet insulation behavior, manufacturability, and bankability.

The key point of this work is a practical circular economy argument:

- Repowering will happen (for reliability and/or upgrading reasons).

- Therefore, the sustainability result depends on whether the module can be cleanly and quickly dismantled, enabling high-value reuse and low-emission processing during repeated replacement.
- A demountable PDMS gel architecture is therefore an enabling technology for sustainable repowering in demanding climates and not an esthetic design feature [26].

Conventional PV panel/module recycling is often limited by laminated-stack separation, where polymer layers (encapsulants and backsheets) constrain clean component recovery and can require energy-intensive thermal steps and/or chemical processing, producing off-gas and/or liquid residues that must be treated [26,28]. Under frequent repowering, these process burdens scale approximately with the throughput multiplier M (Equation (1)): for $R = 5$ years, the polymer separation challenge is encountered ~6× over a 30-year horizon (Table 2; Figure 7). Therefore, an architecture that enables room-temperature delamination and high direct reuse (as reported for soft PDMS gel lamination [26]) directly targets the primary scaling driver created by rapid repowering.

Cell Replacement During Repowering

A demountable architecture also changes what "repowering" can mean. In conventional lamination, modules are effectively sealed irreversibly, and repowering involves discarding the entire module. With room-temperature delamination and a re-enterable laminate architecture, repowering can be structured to reuse the non-cell components (the glass, frame, and junction box where applicable) and replace the cell string set with higher-efficiency cells during scheduled repowering cycles. This upgrade logic is also consistent with recent semitransparent perovskite agrivoltaic concepts, where simulations of full PSC integration indicated a positive annual greenhouse energy balance [37]. This is a logical engineering consequence of the demounting ability, and the high reuse fractions reported for soft gel lamination support the feasibility of component reuse in practice [26]. (The exact implementation depends on the manufacturing and safety qualifications, but the design direction is clear: repowering becomes cleaner when disassembly and reuse are incorporated from the start.)

Any repowering ready module architecture must be evaluated against the relevant safety and reliability requirements (e.g., wet insulation behavior, mechanical durability, damp–heat, thermal cycling, UV exposure, and long-term electrical safety) to support bankability and operational acceptance. This study does not use a full-cost model or standard qualification program; instead, we identify where the environmental leverage lies under repeated repowering and which performance attributes must be verified for implementation at scale.

4.5. End-of-Life Governance: Why "Certified Clean Recycling" Is Required Under Replacement

Repeatedly repowering impacts collection and recycling systems. The end-of-life management literature demonstrates that the recycling performance varies widely on the basis of the process choice and that the difference between high-quality recovery and low-grade handling is important for environmental outcomes [27]. When repowering occurs every five years, EoL routing is not a distant issue; it is a recurring operational requirement.

In this context, the critical requirement is not that "recycling exists" but that the processing route is documented and auditable and that direct emissions and hazardous residues are minimized under repeated throughput. In practice, this means traceable mass balance, transparent process steps (thermal/chemical/mechanical), and a demonstrated ability to recover high-value fractions consistently at scale [26,28].

Demountable PDMS gel designs may support lower-emission and more auditable processing because they can reduce reliance on aggressive thermal or chemical laminate-separation steps [26].

4.6. Embodied Emissions: Repetition Dominates First-Order Scaling

The total greenhouse gas emissions associated with PV electricity depend on the energy supply options and manufacturing assumptions [28]. However, under frequent repowering, the dominant first-order driver is the number of module sets installed within the planning horizon. A 5-year repowering practice repeats manufacturing and transport cycles six times in 30 years. Even if manufacturing becomes cleaner in the future, the repetition penalty remains large unless the repowering intervals increase or the repowering process shifts toward component reuse enabled by demountable designs [26]. This is precisely why Equation (1) is used as the simplest "sanity check". Even with uncertain LCA inventories, the scaling term $M = H/R$ sets the minimum repetition burden. Therefore, short repowering intervals should be treated as a core parameter in sustainability planning and not as a marginal detail.

4.7. Practical Synthesis

For demanding climates where repowering after ~5 years occurs despite a ~30-year expectation, a technically grounded sustainability position can be succinctly stated as follows:

1. We assume that repowering will occur and plan the EoL capacity accordingly (repeated surges).
2. Do not rely on dry-only insulation screening; use risk-based wet condition verification to avoid latent wet failures and to reduce recurring sunrise trips [23,25].
3. Treat delamination-driven escalation as an inverter-level risk, not merely as module cosmetic degradation [24].
4. Repowering ready module construction that enables clean disassembly and high-value reuse, specifically soft PDMS gel lamination, enabling room-temperature delamination and high direct reuse, should be adopted [26].
5. Require certified auditable low-emission EoL routing consistent with EoL management best practices [27,29].

4.8. Summary of the Main Reasons for Rapid 5-Year Repowering

Table 4 summarizes illustrative field reports of high degradation rates in demanding climates [7–11] over short exposure periods. The purpose is not to claim that most PV power plants in demanding/tropical climates fail within less than 5 years. Rather, these reports show that, under some climatic and operational conditions, degradation can become substantial within only a few years and can therefore contribute to earlier repowering pressure.

Table 4. Illustrative reported cases of high early degradation in demanding climates.

Location **Ref. No.**	**Morocco** **[11]**	**India** **[7]**	**Thailand** **[8]**	**Senegal** **[9]**
Annual degradation	−2.6%	−20%	−2.7%	−2.96%
Exposure	3 years	2.5 years	3 years	4 years

Note: The cases in Table 4 are illustrative site-level examples used to motivate boundary conditions for early repowering; they should not be interpreted as representative degradation rates for the global PV fleet.

At the same time, rapid repowering is not driven by degradation alone. Safety and reliability considerations are important as well, especially where wet-condition insulation failures, recurrent inverter trips, and delamination-driven escalation affect plant availability [23,24]. In addition, economic upgrading incentives may further shorten the practical repowering interval, particularly where higher module efficiency can improve output within fixed area and grid-connection constraints [1–5].

Accordingly, the ~5-year case used in this manuscript should be interpreted as a severe-case scenario for demanding sites.

Early 10-year repowering was evaluated in 2021 in an IEA report [3]. In the moderate climate of Europe, a PV power plant repowering within 10–15 years is now common (although few years ago, it was negligible). This is a short repowering period compared with the declared 25–30 years of PV panel longevity. Aggressive/intensive financial optimization could explain this effect (especially in combination with rapid degradation). Therefore, in a demanding/tropical climate, ~5-year repowering of PV power plants is a possibility.

4.9. Limitations and Future Research Directions

This study provides a scenario-based transparent scaling analysis rather than a plant-specific predictive model or a full LCA. The main limitations are as follows. (i) The repowering interval R is treated as an exogenous scenario rule (Table 2) and not as an optimized economic decision. (ii) BOS impacts and logistics are not modeled quantitatively. (iii) The Weibull baseline (Equation (2)) is used to contextualize conventional lifetime loss modeling [29], but the dominant effect under rapid repowering is governed by the discrete replacement rule through Equation (1). (iv) We do not provide a detailed technoeconomic comparison of recycling pathways, including CAPEX/OPEX and the market value of recovered fractions. Future work should parameterize BOS replacement fractions and transport distances explicitly; however, whenever BOS turnover accompanies module turnover, this is expected to strengthen rather than weaken the present conclusion.

Future work should therefore focus on (a) collecting larger multisite datasets on wet condition insulation behavior and inverter trip patterns to estimate the probability of rapid repowering in different climates, (b) developing uncertainty bounds for repower-driven waste projections beyond simple interval sensitivity (Table 3), (c) pilot-scale demonstrations of repowering ready module disassembly and component reuse using PDMS gel architectures, including repeatability at industrial throughput, and (d) systematic evaluation of the long-term safety and durability performance under relevant test sequences and field validation to support the bankability of disassemblable designs.

5. Conclusions

The key contribution of this study is the sustainable solution for rapid (~5-year) PV repowering: effective and clean end-of-life processing enabled by disassemblable module designs—specifically, soft PDMS (polydimethylsiloxane) gel encapsulation—that allows for room-temperature delamination, high-efficiency recycling, and high direct reuse [26]. This approach targets the environmental burden created when repowering causes increased PV waste.

1. PV projects are typically associated with ~30-year module service life expectations; however, in demanding climates, repowering after ~5 years is a practical and economically feasible [23] reality for a subset of plants.
2. Intensive financial optimization is a decisive factor in the rapid repowering of solar PV farms (especially in combination with rapid degradation).
3. The five-year full-replacement case is the severe scenario addressed in this work, supported by independent field evidence that humidity-dependent ground-impedance deterioration and inverter shut-down risk can emerge on this timescale in real utility-scale plants [12–14].

4. Using a transparent scenario model over a 30-year horizon, we show that the primary calling term is the throughput multiplier (Equation (1)). For $R = 5$ years, $M = 6$ (Table 2), increased waste is produced during repowering events, rather than during a single end-horizon decommissioning wave (Figure 6). A compact sensitivity analysis (Table 3) demonstrates that this effect remains strong for other short replacement intervals and prevents the deterministic interpretation of "5 years" as universal.
5. If repowering after ~5 years occurs despite a 30-year expectation, sustainability requires two practical measures: (i) very clean low-emission end-of-life processing enabled by repowering ready disassemblable module architectures (with soft PDMS gel encapsulation as a key enabler) [26,27] and (ii) risk-based wet condition insulation verification to reduce latent wet failures and operational escalation.

Author Contributions: Conceptualization, V.P.; methodology, V.P. and M.K.; formal analysis, V.P.; writing—original draft preparation, V.P.; writing—review and editing, V.P. and M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Villena Ruiz, R.; Martín Martínez, S.; Honrubia Escribano, A.; Javier Ramírez, F.; Gómez Lázaro, E. Solar PV power plant revamping: Technical and economic analysis of different alternatives for a Spanish case. *J. Clean. Prod.* **2024**, *446*, 141439. [CrossRef]
2. Jean, J.; Woodhouse, M.; Bulović, V. Accelerating photovoltaic market entry with module replacement. *Joule* **2019**, *3*, 2824–2841. [CrossRef]
3. IEA PVPS. T12. Available online: https://iea-pvps.org/wp-content/uploads/2021/11/IEA_PVPS_T12_Preliminary-EnvEcon-Analysis-of-module-reuse_2021_report.pdf (accessed on 7 February 2026).
4. Fraunhofer Institute for Solar Energy Systems ISE. *Photovoltaics Report*; Fraunhofer Institute for Solar Energy Systems ISE: Freiburg, Germany, 2025. Available online: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html (accessed on 7 February 2026).
5. IRENA. *Renewable Power Generation Costs in 2020*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2021. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf (accessed on 7 February 2026).
6. Libra, M.; Mrazek, D.; Tyukhov, I.; Severova, L.; Poulek, V.; Mach, J.; Subrt, T.; Beranek, V.; Svoboda, R.; Sedlacek, J. Reduced real lifetime of PV panels—Economic consequences. *Sol. Energy* **2023**, *259*, 229–234. [CrossRef]
7. Sharma, V.; Chandel, S.S. A novel study for determining early life degradation of multi-crystalline-silicon photovoltaic modules observed in western Himalayan In-dian climatic conditions. *Sol. Energy* **2016**, *134*, 32–44. [CrossRef]
8. Le, N.T.; Asdornwised, W.; Chaitusaney, S.; Benjapolakul, W. Annual Degradation Rate Analysis of Mono-Si Photovoltaics Systems in Thailand Using the Mixed Effects Method. *IEEE Access* **2021**, *9*, 101335–101343. [CrossRef]
9. Ndiaye, A.; Kébé, C.M.F.; Charki, A.; Ndiaye, P.A.; Sambou, V.; Kobi, A. Degradation evaluation of crystalline silicon photovoltaic modules after a few operation years in a tropical environment. *Sol. Energy* **2014**, *103*, 70–77. [CrossRef]
10. Bouraiou, A.; Hamouda, M.; Chaker, A.; Mostefaoui, M.; Lachtar, S.; Sadok, M.; Boutasseta, N.; Othmani, M.; Issam, A. Analysis and evaluation of the impact of climatic conditions on photovoltaic module performance in the desert environment. *Energy Convers. Manag.* **2015**, *106*, 1345–1355. [CrossRef]
11. Bouaichi, A.; Merrouni, A.A.; Hajjaj, C.; Messaoudi, C.; Ghennioui, A.; Benlarabi, A.; Ikken, B.; El Amrani, A.; Zitouni, H. In situ evaluation of early PV module degradation of various technologies under harsh climatic conditions: The case of Morocco. *Renew. Energy* **2019**, *143*, 1500–1518. [CrossRef]

12. Buerhop Lutz, C.; Stroyuk, O.; Pickel, T.; Winkler, T.; Hauch, J.; Peters, I.M. PV modules and their backsheets—A case study of a multi MW PV power station. *Sol. Energy Mater. Sol. Cells* **2021**, *231*, 111295. [CrossRef]
13. Lutz, C.B.; Lüer, L.; Stroyuk, O.; Hauch, J.; Peters, I.M. Dynamics of backsheet driven insulation issues. *Sol. Energy Mater. Sol. Cells* **2023**, *257*, 112398. [CrossRef]
14. Hassan Daher, D.; Gaillard, L.; Ménézo, C. Experimental Assessment of Long-Term Performance Degradation for a PV Power Plant Operating in a Desert Maritime Climate. *Renew. Energy* **2022**, *187*, 44–55. [CrossRef]
15. Simsek, E.; Williams, M.J.; Pilon, L. Effect of dew and rain on photovoltaic solar cell performances. *Sol. Energy Mater. Sol. Cells* **2021**, *222*, 110908. [CrossRef]
16. Hernández, J.; Vidal, P.G.; Medina, A. Characterization of the insulation and leakage currents of PV generators: Relevance for human safety. *Renew. Energy* **2010**, *35*, 593–601. [CrossRef]
17. Roy, J.N. Modeling of insulation characteristics of solar photovoltaic (SPV) modules. *Sol. Energy* **2015**, *120*, 1–8. [CrossRef]
18. Buerhop, C.; Stroyuk, O.; Zöcklein, J.; Pickel, T.; Hauch, J.; Peters, I.M. Wet leakage resistance development of modules with various backsheet types. *Prog. Photovolt. Res. Appl.* **2022**, *30*, 938–947. [CrossRef]
19. Stroyuk, O.; Güttler, C.; Buerhop Lutz, C.; Hauch, J.; Peters, I.M. Identification of Backsheet Type of Silicon PV Modules from Encapsulant Fluorescence Images. *ACS Appl. Energy Mater.* **2023**, *6*, 2340–2346. [CrossRef]
20. Kempe, M.D.; Lyu, Y.; Kim, J.H.; Felder, T.; Gu, X. Fragmentation of photovoltaic backsheets after accelerated weathering exposure. *Sol. Energy Mater. Sol. Cells* **2021**, *226*, 111044. [CrossRef]
21. Ketjoy, N.; Mensin, P.; Chamsa Ard, W. Impacts on insulation resistance of thin film modules: A case study of flooding of a photovoltaic power plant in Thailand. *PLoS ONE* **2022**, *17*, e0274839. [CrossRef]
22. Luo, W.; Khoo, Y.S.; Hacke, P.; Naumann, V.; Lausch, D.; Harvey, S.P.; Singh, J.P.; Chai, J.; Wang, Y.; Aberle, A.G.; et al. Potential induced degradation in photovoltaic modules: A critical review. *Energy Environ. Sci.* **2017**, *10*, 43–68. [CrossRef]
23. Poulek, V.; Beranek, V.; Finsterle, T.; Kozelka, M. Dry pass, wet fail: Ground impedance testing of field aged PV modules—Implications for repowering/revamping within 5–10 years and for environmental sustainability. *Sustainability* **2026**, *18*, 1212. [CrossRef]
24. Poulek, V.; Safrankova, J.; Cerna, L.; Libra, M.; Beranek, V.; Finsterle, T.; Hrzina, P. PV panel and PV inverter damages caused by combination of edge delamination, water penetration, and high string voltage in moderate climate. *IEEE J. Photovolt.* **2021**, *11*, 561–565. [CrossRef]
25. *IEC 61215-2:2021*; Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval—Part 2: Test Procedures (MQT 15: Wet Leakage Current Test). International Electrotechnical Commission: Geneva, Switzerland, 2021. Available online: https://webstore.iec.ch/en/publication/61350 (accessed on 7 February 2026).
26. Poulek, V.; Beranek, V.; Kozelka, M.; Finsterle, T. Environmentally sustainable recycling of photovoltaic panels laminated with soft polysiloxane gels: Promoting the circular economy and reducing the carbon footprint. *Sustainability* **2025**, *17*, 8167. [CrossRef]
27. Papamichael, I.; Voukkali, I.; Jeguirim, M.; Argirusis, N.; Jellali, S.; Sourkouni, G.; Argirusis, C.; Zorpas, A.A. End of life management and recycling on PV solar energy production. *Energies* **2022**, *15*, 6430. [CrossRef]
28. Reich, N.H.; Alsema, E.A.; van Sark, W.G.J.H.M.; Turkenburg, W.C.; Sinke, W.C. Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options. *Prog. Photovolt. Res. Appl.* **2011**, *19*, 603–613. [CrossRef]
29. IRENA; IEA-PVPS. End-of-Life Management: Solar Photovoltaic Panels. 2016. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf (accessed on 7 February 2026).
30. Królikowski, M.; Fotek, M.; Żach, P.; Michałowski, M. Development of a Recycling Process and Characterization of EVA, PVDF, and PET Polymers from End-of-Life PV Modules. *Materials* **2024**, *17*, 821. [CrossRef]
31. Heubl, B. Spotlight on a solar scandal: Millions of solar PV panels could fail or degrade prematurely and may even be at risk of fires. But no one knows exactly where they are or how big the problem is. Rectifying the faults could cost billions. E&T investigates. *Eng. Technol.* **2020**, *15*, 38–41. [CrossRef]
32. Anagha, E.R.; Kulkarni, S.V.; Shiradkar, N. Development of a Characterization Technique to Effectively Detect Latent Insulation Defects in the Field-Deployed PV Modules. *Sol. Energy Mater. Sol. Cells* **2025**, *292*, 113761. [CrossRef]
33. Ketola, B.M.; McIntosh, K.R.; Norris, A.; Tomalia, M.K. Silicones for photovoltaic encapsulation. In Proceedings of the 23rd European Photovoltaic Solar Energy Conference, Valencia, Spain, 1–5 September 2008; pp. 2969–2973. Available online: https://www.researchgate.net/publication/266496217_Silicones_for_Photovoltaic_Encapsulation (accessed on 7 February 2026).
34. Hara, K.; Ohwada, H.; Furihata, T.; Masuda, A. Durable Crystalline Si Photovoltaic Modules Based on Silicone-Sheet Encapsulants. *Jpn. J. Appl. Phys.* **2018**, *57*, 027101. [CrossRef]
35. Lopez-Garcia, J.; Pozza, A.; Sample, T. Analysis of crystalline silicon PV modules after 30 years of outdoor exposure. In Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany, 14–18 September 2015; pp. 1839–1845. [CrossRef]

36. Dintcheva, N.T.; Morici, E.; Colletti, C. Encapsulant Materials and Their Adoption in Photovoltaic Modules: A Brief Review. *Sustainability* **2023**, *15*, 9453. [CrossRef]
37. Spampinato, C.; Valastro, S.; Calogero, G.; Smecca, E.; Mannino, G.; Arena, V.; Balestrini, R.; Sillo, F.; Cinà, L.; La Magna, A.; et al. Improved radicchio seedling growth under CsPbI3 perovskite rooftop in a laboratory-scale greenhouse for Agrivoltaics application. *Nat. Commun.* **2025**, *16*, 2190. [CrossRef] [PubMed]

https://doi.org/10.3390/su18073599