

Rapid 5-year Repowering of Photovoltaic Power Plants in Demanding Climates: Effective, very clean recycling and disassemblable PDMS-gel encapsulation to reduce environmental impact

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Abstract

Photovoltaic (PV) plants are often planned for a 25–30-year module service life, yet field experience in demanding climates indicates that effective lifetimes can be much shorter and that dry-only insulation checks may underestimate wet-condition risk. Repowering after ~5 years can restore yield and reduce operational trips, but it compresses PV waste and manufacturing into repeated surges. We review evidence that moisture (dew/rain), especially around sunrise, can activate leakage pathways and reduce insulation resistance (ground impedance, Risol), including IEC-conformant wet leakage testing of field-aged modules showing a dry-pass/wet-fail population. We also summarise a delamination-driven pathway from water ingress to discharge channels, inverter shut-down and potential damage. To mitigate environmental impacts under frequent repowering, we discuss repowering-ready module designs using soft polydimethylsiloxane (PDMS) gel encapsulation enabling room-temperature delamination, very clean high-efficiency recycling and high component reuse. A transparent 30-year scenario model illustrates “year-5” waste surges and a 6× module throughput multiplier under 5-year repowering. We conclude that demanding-climate sites with rapid repowering should combine risk-based wet-condition insulation verification with documented and auditable low-emission end-of-life processing enabled by disassemblable module architectures.

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

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1. Introduction

PV is widely communicated and financed with an implicit ~30-year module service-life expectation, yet a subset of plants in demanding climates are repowered after ~5 years. This is not a rhetorical exaggeration: where repeated inverter trips, delayed morning startup, and escalating downtime become routine, early replacement becomes the pragmatic asset-management choice. In parallel, ongoing improvements in module

efficiency and declining costs reinforce the economic incentive to replace earlier, especially where area and grid connection are fixed constraints.

The sustainability consequence is mechanical: if repowering occurs every 5 years, then within a 30-year planning horizon 6 complete module sets are deployed and decommissioned. That creates repeated waste surges and repeated manufacturing demand. In other words, the sustainability outcome is governed by the repowering interval, not by the nominal service-life expectation printed in a datasheet.

This paper is written with 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. The goal is therefore not to argue whether repowering “should” happen, but to clarify why it happens, why wet-condition insulation is central, and how the environmental impact can be reduced when repowering becomes frequent. The central technical message is that field screening is commonly performed in dry conditions for speed, while 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 high-efficiency and low-emission, preferably enabled by repowering - ready module construction.

1.1. Repowering as an operational reality, not an exception

Solar PV plant revamping and repowering have been analysed as technical and economic decisions with multiple alternatives, strongly dependent on site constraints and assumptions [1]. Module replacement has also been discussed as a mechanism that can accelerate technology upgrading and market entry, by allowing a mature BOS and grid connection to host higher-performance modules [2]. At fleet scale, such decisions matter more as global deployment expands and the installed base ages [3]. Technology reporting confirms continuing efficiency improvements and module power increases [4], while cost assessments show PV as a competitive generation option in many regions [5]. These trends make repowering attractive even when the existing plant is not yet “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 high opportunity cost. When that cost accumulates early, repowering becomes the simplest method to restore stable operation. 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.

1.2. Short effective service life in demanding climates

Reduced real lifetime has been discussed explicitly together with its economic consequences, showing how shorter service life changes project economics and replacement strategy [6]. 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]. Field exposure of crystalline-silicon modules has shown performance evolution under real outdoor conditions that can

diverge from simplified planning assumptions [8]. Degradation evaluations after only a few years in tropical environments show that early degradation and defect accumulation can be significant depending on climate and construction [9]. Similar conclusions appear in studies of harsh desert and arid deployments, where climatic stressors affect module behaviour and performance [10]. In-situ evaluation under harsh Moroccan conditions likewise reports early degradation of various technologies [11].

These studies do not imply that all PV plants will repower after five years. They do establish, however, that in demanding climates the effective service life can be shortened enough that early replacement becomes practical, and that in those cases sustainability analysis must reflect the real replacement interval rather than a nominal expectation.

1.3. Wet-condition insulation is routinely relevant and commonly under-screened

Insulation resistance (ground impedance, R_{isol}) between PV DC circuits and accessible conductive parts/ground is a key safety and reliability metric: low R_{isol} can trigger inverter protection and indicates potentially hazardous leakage, and wet operation is routine because dew, fog, and rain films commonly form (especially around sunrise), while colder modules can also raise open-circuit voltage [12–14]. Although IEC 61215-2 defines a wet leakage current compliance test (MQT 15) using a resistance–area product criterion ($R_{wet} \times A \geq 40 \text{ M}\Omega\cdot\text{m}^2$ for modules $> 0.1 \text{ m}^2$) [15], this is typically used for type approval of new designs rather than routine screening of field-aged modules, where O&M practice often defaults to faster dry checks. That convenience can misrepresent risk because moisture activates surface/edge leakage pathways and because degradation at polymeric interfaces (frame edges, backsheets, junction boxes) can create wet-activated conduction routes that differ across backsheet constructions and evolve over time [16–20], with plant-scale impacts documented under severe moisture exposure such as flooding [21]. High-voltage stress mechanisms (e.g., PID) may further interact with string voltage and leakage conditions, particularly in harsh environments [22]. 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 latent trip risk during routine wet mornings: modules appear acceptable in dry screening yet fail under wet conditions. Figure 1 summarises the outcome categories at a conceptual level based on published statistics.

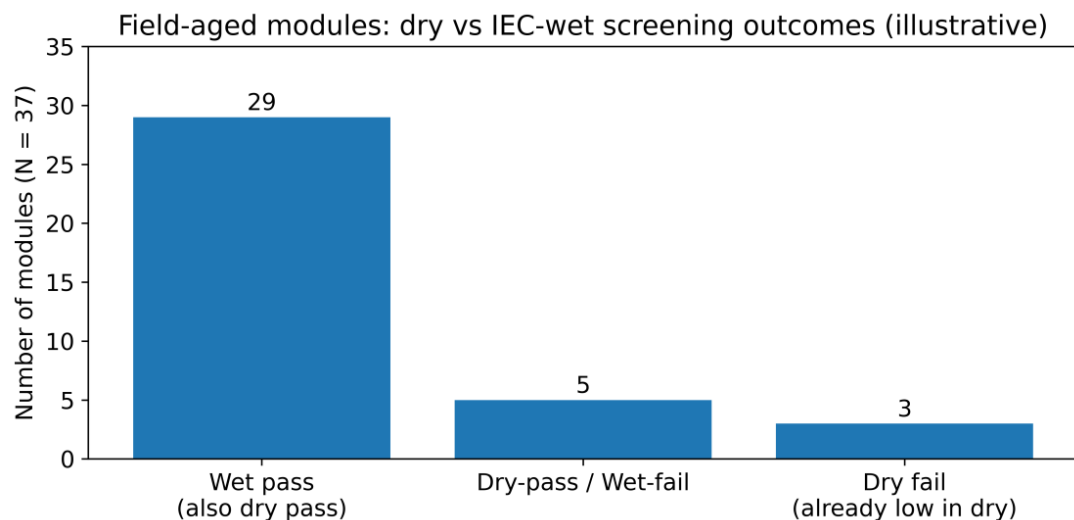


Figure 1. Field-aged modules: dry vs IEC-wet screening outcomes (illustrative; based on published statistics in [23]).

1.4. Sunrise window: wet surfaces can coincide with high DC voltage

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

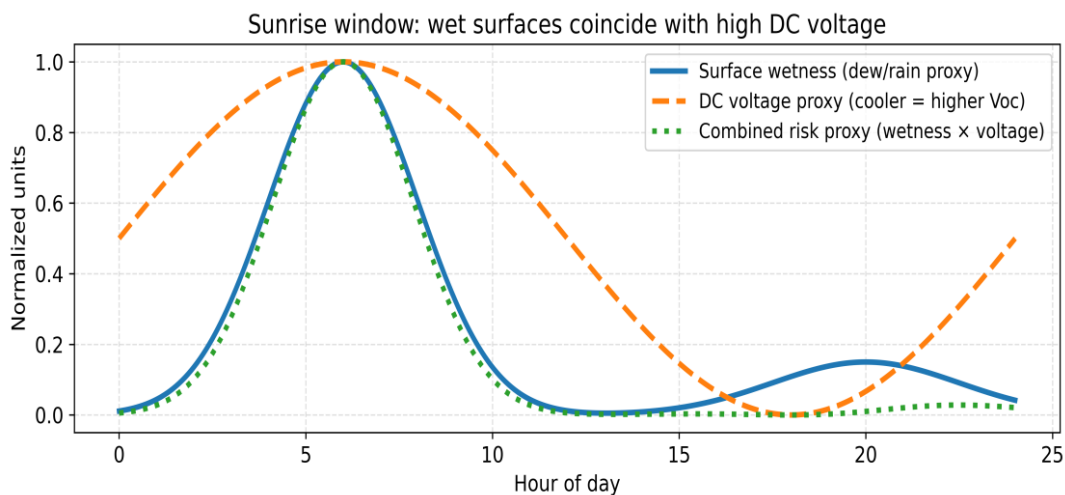


Figure 2. Sunrise window: wet surfaces coincide with high DC voltage (stylised proxy; supported by [12–14]).

1.5. Failure escalation: from delamination to inverter-level impacts

Wet leakage issues are not only nuisance trips. A documented field pathway links edge delamination to water penetration and the formation of discharge channels between string conductors and grounded frames, leading to 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 increased operational risk. This “multiplication effect” shifts repowering from an economic optimisation into a risk-control decision. Figure 3 summarises the escalation chain, from edge delamination and water ingress to discharge channels, Risol reduction, inverter events, and downtime/damage.

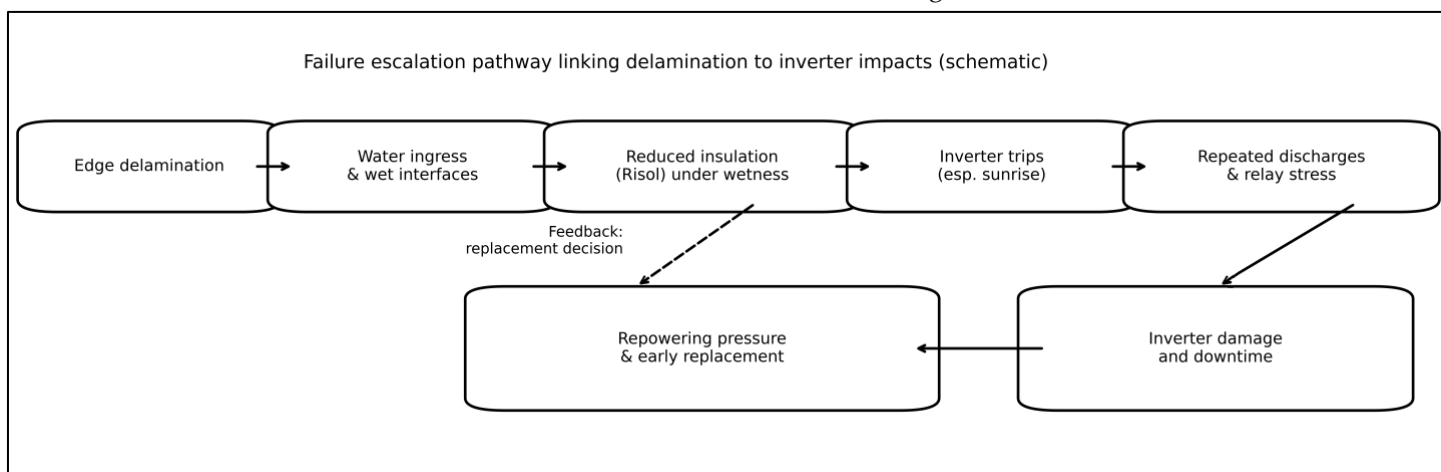


Figure 3. Failure escalation pathway linking delamination to inverter impacts (schematic; based on [24]).

1.6. Repowering pressure is also technology-driven efficiency improvements

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

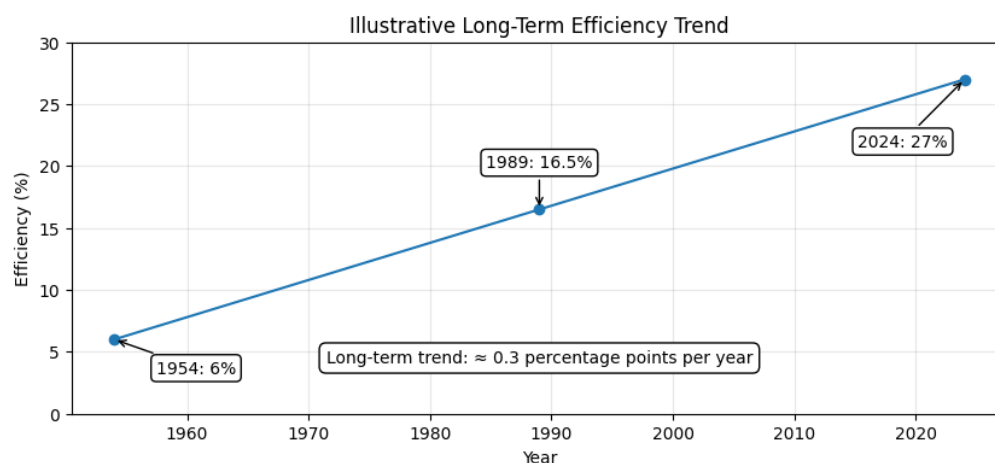


Figure 4. Illustrative long-term efficiency trend (absolute percentage points; consistent with [4]).

1.7. Objectives and paper logic

This paper adopts a practical stance: repowering after ~5 years will occur for 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.

The objectives are therefore:

1. To frame wet-condition insulation behaviour as a routinely relevant operational driver, and to document why dry-only screening can miss wet failures [15,23].
2. To summarise 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 waste timing (“surges”), module throughput multipliers, and manufacturing diversion.
4. To argue, on technical and sustainability grounds, that repowering-ready module construction enabling clean disassembly and high direct reuse—specifically soft PDMS-gel encapsulation—reduces the environmental burden of inevitable repowering [25].
5. To place the above in the context of EoL management and embodied-emissions variability [27,28].

2. Materials and Methods

2.1. Evidence base

The paper synthesises published evidence on: wet leakage standards and field-aged wet insulation [15,23]; dew/rain moisture relevance [12]; insulation safety and modelling [13,14]; backsheet-driven insulation issues [16–20]; flooding impacts [21]; PID under high voltages [22]; delamination-driven inverter impacts [24]; and demountable encapsulation and recycling using soft PDMS/polysiloxane gels [25]. Sustainability discussion is grounded in EoL management literature [26] and in established analysis of greenhouse-gas emissions associated with PV electricity [27].

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). BOS is assumed largely reusable during repowering; BOS impacts are addressed qualitatively in limitations.

2.3. Scenarios

We define three scenarios:

- **S0 (rapid repowering):** full module replacement every 5 years → 6 complete module sets over 30 years.
- **S1 (sensitivity):** full module replacement every 10 years → 3 complete module sets over 30 years.
- **S2 (baseline expectation):** no replacement within 30 years → 1 module set over 30 years.

The central comparison is S0 versus S2, because it captures the mismatch between the ~30-year expectation and the practical ~5-year repowering behaviour.

2.4. Indicators

Three indicators follow directly from the scenarios:

1. **Waste timing:** replacement events create discrete waste “surges” over time.
2. **Module throughput multiplier:** number of module sets installed per 30 years (mechanical multiplier for manufacturing and EoL flows).
3. **Stylised manufacturing diversion:** replacement demand consumes factory output that could otherwise supply new deployment.

These indicators are deliberately first-order: they quantify scale and timing without requiring a detailed plant-specific optimisation.

3. Results

3.1. Wet-condition operation creates a sunrise risk window

Moisture films (dew, rain) tend to peak around sunrise, while string voltage can be high because 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 [12–14,23]. The key operational point is not only that wet conditions happen, but that they happen at a time when voltage conditions are unfavourable for insulation margins. Figure 2 provides the stylised proxy of this combined window.

3.2. Dry-only screening can miss wet failures at non-trivial rates

IEC-conformant wet leakage testing of field-aged modules shows that dry measurements can systematically overestimate wet insulation and that a dry-pass/wet-fail population exists [23]. In plant practice this means: a module population may appear acceptable under convenient dry screening yet still generate repeated trips under routine wet mornings. This is consistent with the O&M observation that sunrise events can persist until the real wet-condition leakage pathways are identified. Figure 1 summarises the outcome pattern at a conceptual level.

3.3. Delamination-driven escalation increases repowering pressure

The delamination pathway provides a mechanism for escalation: edge delamination → water ingress → conductive wet interfaces → discharge channel formation to grounded frames → inverter switch-off due to low R_{isol} → repeated discharges stressing protective components → downtime and potentially 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 towards larger replacement campaigns. Figure 3 summarises the mechanism.

3.4. Waste timing: 5-year repowering produces repeated “year-5 surges”

To visualise the discontinuity between a nominal long-life loss progression and a rapid repowering practice, Figure 5a reproduces the Weibull cumulative probability-of-loss curve used in the IRENA/IEA-PVPS PV panel waste model for the regular-loss scenario

(Weibull form $F(t) = 1 - \exp[-(t/T)^\alpha]$, with $T = 30$ years and $\alpha = 5.3759$) and overlays the 5-year repowering trigger adopted here for scenario S0 [28]. Importantly, the original IRENA/IEA-PVPS waste model explicitly excludes repowering; the 5-year threshold is therefore introduced in this study as an exogenous scenario assumption to represent observed rapid repowering practice in demanding climates [28]. Applying this 5-year trigger yields replacement events at years 5, 10, 15, 20, 25, and 30. Under S2, the primary decommissioning event occurs at year 30. Figure 5b translates these events into cumulative waste expressed in module-set equivalents. The result is mechanical: within a 30-year planning horizon, 5-year repowering requires six complete module sets (6× throughput) and therefore generates repeated waste “surges”, rather than a single late-horizon decommissioning wave

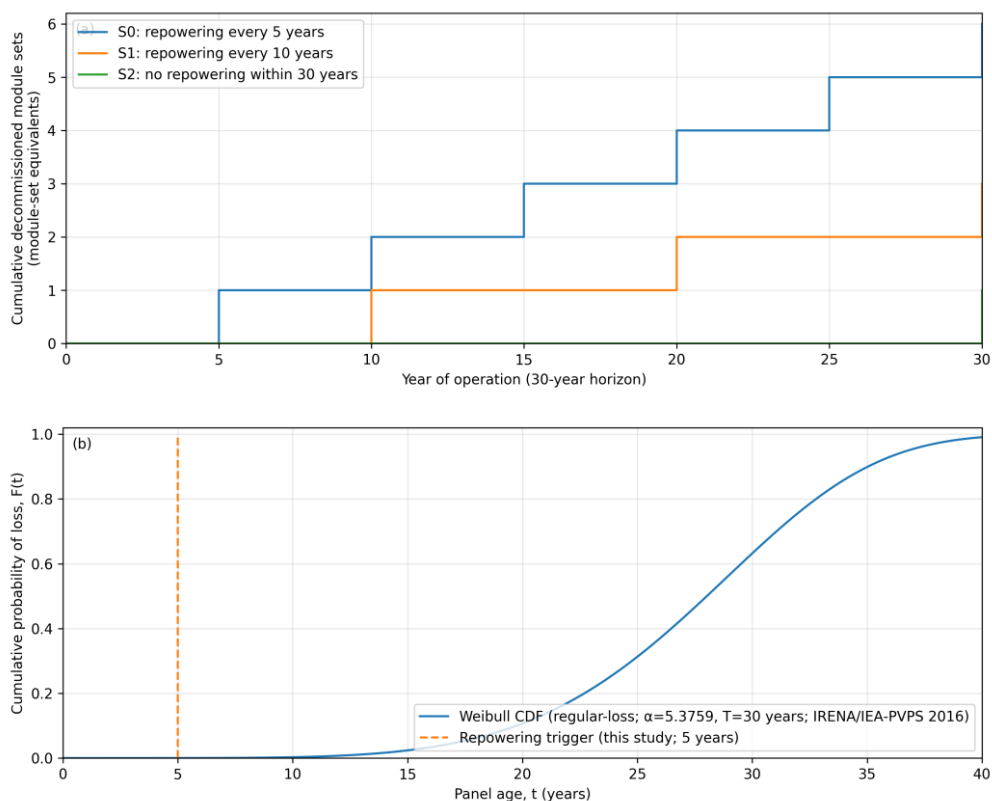


Figure 5. (a) Stylised Weibull cumulative probability-of-loss curve with the repowering trigger used in S0 (5 years, dashed line). (b) Resulting cumulative waste over 30 years expressed in module-set equivalents (“step” increases at each replacement event) [28]

3.5. Module throughput multiplier scales with repowering interval

Figure 6 summarises the number of module sets manufactured per 30-year service. The multiplier is again mechanical: S0 corresponds to 6 module sets (6×), S1 to 3 sets (3×), and S2 to 1 set (1×). This multiplier is the first-order driver of repeated manufacturing, transport, and EoL processing under short repowering cycles.

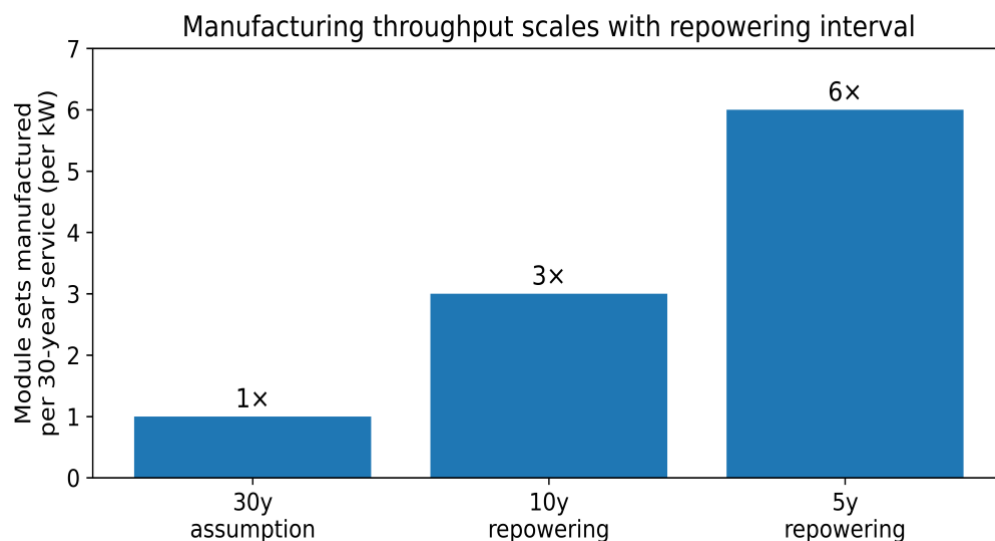


Figure 6. Manufacturing throughput scales with repowering interval (module sets per 30-year service).

3.6. Manufacturing-capacity constraint: replacement demand diverts output from new deployment

At system scale, replacement demand competes with new deployment for manufacturing output. The stylised factory model in Figure 7 illustrates the effect: if a fixed manufacturing capacity supplies both growth and replacement, then short repowering intervals cause earlier saturation of “new fleet supplied” because output is increasingly consumed by replacement. This is an energy-transition constraint when replacement demand becomes substantial, because it reduces how much net new capacity can be added for a given manufacturing base.

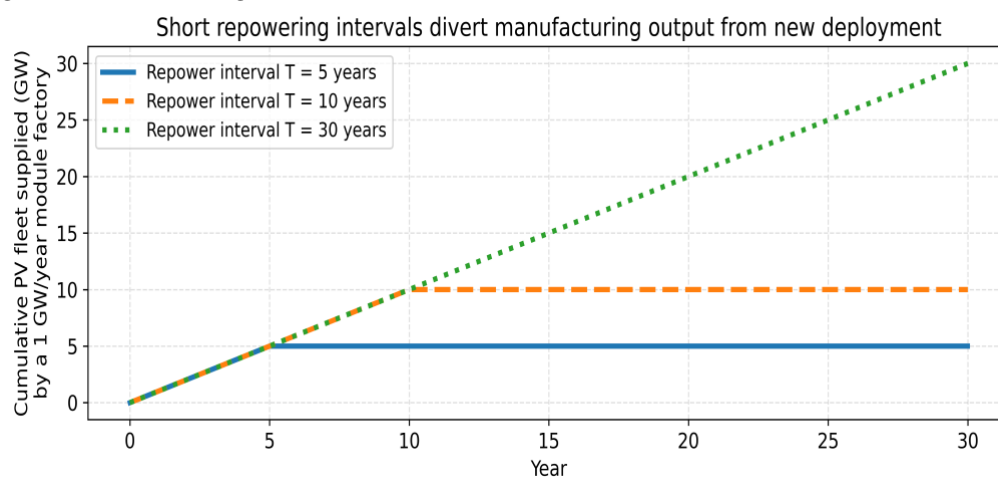


Figure 7. Short repowering intervals divert manufacturing output from new deployment (stylised illustration).

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 module expectation, but in practice is repowered after ~5 years, then sustainability analysis based on the nominal expectation will understate both waste and repeated manufacturing. The difference is not subtle:

5-year repowering 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 repowering-prone after ~5 years, and how can the environmental impact be reduced when repowering becomes the practical path? The evidence reviewed here supports two technical drivers that are consistent with field observations: (i) wet-condition insulation behaviour 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 pressure (efficiency gains) [4], these drivers make repowering after ~5 years an expected practice for a subset of demanding sites.

4.2. Wet-condition insulation verification: a practical lever, not a laboratory detail

The fact that IEC wet leakage testing is primarily used for type approval [15] while field screening is commonly dry creates a practical gap. Wet operation is routine, and field-aged evidence shows that dry-only screening can miss wet failures [23]. In demanding climates, and particularly where sunrise trip patterns occur, wet-condition insulation verification should be treated as a risk-based O&M tool.

This does not require turning every plant into a laboratory. 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:

- repeated sunrise trips and delayed morning start-up,
- R_{isol} alarms correlated with dew/rain events,
- visible edge/interface degradation, and
- module populations where backsheet family and ageing history imply higher leakage susceptibility [16–20].

The supporting literature on backsheet-driven insulation issues [16–20], flooding [21], and high-voltage degradation mechanisms such as PID [22] reinforces 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 burden. Under those conditions, full replacement campaigns become the 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, delamination pathways) and the end-of-life processing of repeated surges.

4.4. Repowering-ready circular module construction: why soft PDMS gels matter 312

If repowering after ~5 years is reality for a segment of the fleet, then the sustainability 313
problem is not only “how to recycle more”, but “how to repower without creating 314
high-emission waste handling and low-value disposal”. 315

Here the circular design choice becomes central. Soft PDMS/polysiloxane gel 316
lamination has been reported as an approach that enables **room-temperature mechanical** 317
delamination, high recycling efficiency, and high direct reuse fractions, while avoiding 318
high-temperature burning and aggressive chemical etching [25]. In that framework, a large 319
portion of the module mass can be recovered as reusable components rather than being 320
downcycled or disposed, and processing time can be reduced (rapid disassembly) [25]. 321
Separate work on silicone-gel-laminated modules reports very low degradation rates over 322
multi-decade observation and supports the general claim of high stability for gel-based 323
encapsulation [25]. 324

The key point for this manuscript is not a theoretical circular-economy argument; it 325
is a practical one: 326

- **Repowering will happen** (for reliability and/or upgrading reasons). 327
- Therefore, the sustainability result depends on whether the module can be cleanly 328
and quickly dismantled, enabling high-value reuse and low-emission processing 329
during repeated surges. 330
- A demountable PDMS-gel architecture is therefore not an aesthetic design feature; it 331
is an enabling technology for sustainable repowering in demanding climates [25]. 332

Cell replacement during repowering 333

A demountable architecture also changes what “repowering” can mean. In 335
conventional lamination, modules are effectively sealed irreversibly; repowering means 336
discarding the entire module. With room-temperature delamination and a re-enterable 337
laminate architecture, repowering can be structured to **reuse the non-cell components** 338
(glass, frame, junction box where applicable) and replace the cell string set with 339
higher-efficiency cells during scheduled repowering cycles. This is a logical engineering 340
consequence of demount ability; and the high reuse fractions reported for soft gel 341
lamination support the feasibility of component reuse in practice [25]. (The exact 342
implementation depends on manufacturing and safety qualification, but the design 343
direction is clear: repowering becomes cleaner when disassembly and reuse are designed 344
in from the start.) 345

4.5. End-of-life governance: why “certified clean recycling” is required under surges 346

Repeated repowering surges stress collection and recycling systems. End-of-life 347
management literature shows that recycling performance varies widely by process choice 348
and that the difference between high-quality recovery and low-grade handling is material 349
for environmental outcomes [26]. When repowering occurs every five years, EoL routing 350
is not a distant issue; it is a recurring operational requirement. 351

Demountable PDMS-gel designs directly support certified clean processing because 352
they avoid reliance on high-temperature and high-emission methods for separating the 353

laminated. When repeated surges occur, this is precisely the type of process advantage that reduces both direct emissions and waste burden.

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4.6. Embodied emissions: repetition dominates first-order scaling

Absolute greenhouse-gas emissions associated with PV electricity depend on energy supply options and manufacturing assumptions [27]. 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 repowering intervals increase or the repowering process shifts towards component reuse enabled by demountable designs [25].

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 stated succinctly:

1. **Assume repowering will** occur and plan 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 [15,23].
3. **Treat delamination-driven escalation as an inverter-level risk**, not merely as module cosmetic degradation [24].
4. **Adopt 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 [25].
5. **Require certified, auditable low-emission EoL routing** consistent with EoL management best practice [26].

5. Conclusions

The key novelty of this paper is the sustainability solution for rapid (~5-year) PV repowering: very effective, very clean end-of-life processing enabled by disassemblable module design, specifically soft PDMS (polydimethylsiloxane) gel encapsulation that allows room-temperature delamination, high-efficiency recycling, and high direct reuse [25,26]. This approach targets the environmental burden created when repowering compresses PV waste into repeated surges.

1. PV projects are commonly communicated with a ~30-year module service-life expectation, yet in demanding climates repowering after ~5 years is a practical and economically feasible reality for a subset of plants.
2. 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) [25,26]; and (ii) risk-based wet-condition insulation verification to reduce latent wet failures and operational escalation.
3. Wet-condition insulation behaviour is operationally central because PV arrays routinely experience dew/rain wet mornings, and IEC-conform wet testing of field-aged modules demonstrates that dry-only screening can miss a dry-pass/wet-fail population [15,23]. Delamination-assisted water ingress can escalate wet leakage into inverter switch-off and potentially downtime and damage, amplifying the pressure towards early repowering [24]. A transparent scenario model shows that 5-year repowering mechanically multiplies module throughput (6× over 30 years) and produces repeated waste surges, increasing demand for both manufacturing output and EoL capacity.

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References

1. Villena Ruiz, R.; Martín Martínez, S.; Honrubia Escibano, 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. <https://doi.org/10.1016/j.jclepro.2024.141439>
2. Jean, J.; Woodhouse, M.; Bulović, V. Accelerating photovoltaic market entry with module replacement. *Joule* 2019, 3, 2824–2841. <https://doi.org/10.1016/j.joule.2019.08.012>
3. IEA PVPS. Trends in Photovoltaic Applications 2025; International Energy Agency Photovoltaic Power Systems Programme: Paris, France, 2025. Available online: https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS_Trends_2025-.pdf (accessed on 7 February 2026)
4. Fraunhofer ISE. Photovoltaics Report; Fraunhofer Institute for Solar Energy Systems ISE: Freiburg, Germany, updated 31 October 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, UAE, 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. *Solar Energy* 2023, 259, 229–234. <https://doi.org/10.1016/j.solener.2023.04.063>
7. Atsu, D.; Seres, I.; Aghaei, M.; Farkas, I. Analysis of long term performance and reliability of PV modules under tropical climatic conditions in Sub Saharan. *Renew. Energy* 2020, 162, 285–295. <https://doi.org/10.1016/j.renene.2020.08.021>
8. Sastry, O.S.; Saurabh, S.; Shil, S.K.; Pant, P.C.; Kumar, R.; Kumar, A.; Bandopadhyay, B. Performance analysis of field exposed single crystalline silicon modules. *Sol. Energy Mater. Sol. Cells* 2010, 94, 1463–1468. <https://doi.org/10.1016/j.solmat.2010.03.035>
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. <https://doi.org/10.1016/j.solener.2014.02.006>
10. Bouraiou, A.; Hamouda, M.; Chaker, A.; Mostefaoui, M.; Lachtar, S.; Sadok, M.; Boutassetta, 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. <https://doi.org/10.1016/j.enconman.2015.10.073>
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. <https://doi.org/10.1016/j.renene.2019.05.091>
12. 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. <https://doi.org/10.1016/j.solmat.2020.110908>
13. Hernández, J.; Vidal, P.G.; Medina, A. Characterisation of the insulation and leakage currents of PV generators: Relevance for human safety. *Renew. Energy* 2010, 35, 593–601. <https://doi.org/10.1016/j.renene.2009.08.006>
14. Roy, J.N. Modelling of insulation characteristics of solar photovoltaic (SPV) modules. *Sol. Energy* 2015, 120, 1–8. <https://doi.org/10.1016/j.solener.2015.06.036>
15. 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).
16. Buerhop, C.; Stroyuk, O.; Zöcklein, J.; Pickel, T.; Hauch, J.; Peters, I.M. Wet leakage resistance development of modules with various backsheets types. *Prog. Photovolt. Res. Appl.* 2022, 30, 938–947. <https://doi.org/10.1002/ppp.3481>

17. 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. <https://doi.org/10.1016/j.solmat.2021.111295>
18. 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. <https://doi.org/10.1016/j.solmat.2023.112398>
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. <https://doi.org/10.1021/acsaem.2c03532>
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. <https://doi.org/10.1016/j.solmat.2021.111044>
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. <https://doi.org/10.1371/journal.pone.0274839>
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.; Ramakrishna, S. Potential induced degradation in photovoltaic modules: A critical review. *Energy Environ. Sci.* 2017, 10, 43–68. <https://doi.org/10.1039/C6EE02271E>
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. <https://doi.org/10.3390/su18031212>
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. Photovoltaics* 2021, 11, 561–565. <https://doi.org/10.1109/JPHOTOV.2021.3050984>
25. 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. <https://doi.org/10.3390/su17188167>
26. 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. <https://doi.org/10.3390/en15176430>
27. 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. <https://doi.org/10.1002/pip.1066>
28. 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)

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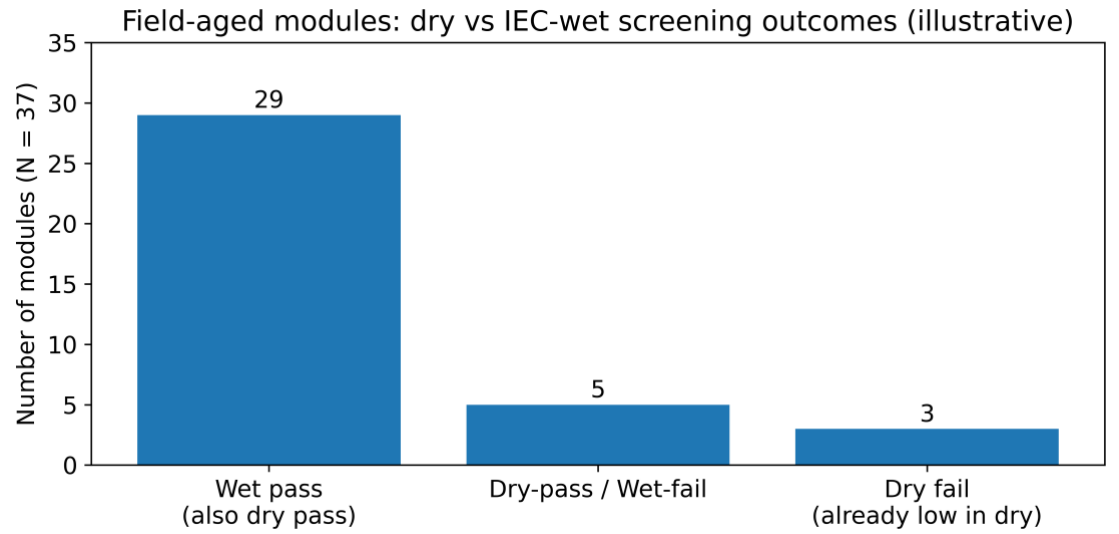


Figure 1. Field-aged modules: dry vs IEC-wet screening outcomes (illustrative; based on published statistics in [23]).

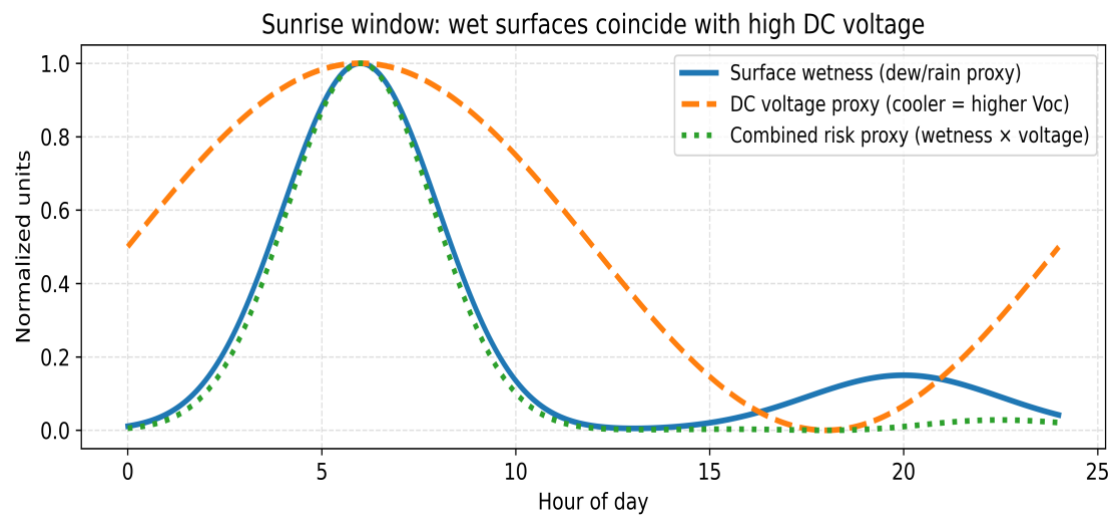
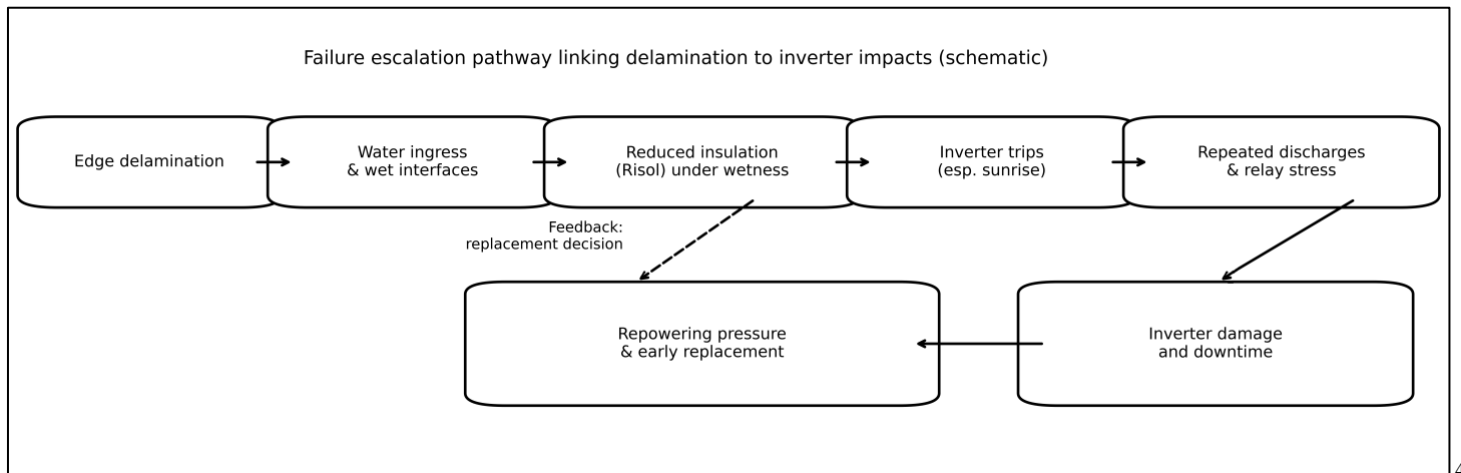


Figure 2. Sunrise window: wet surfaces coincide with high DC voltage (stylised proxy; supported by [12–14]).

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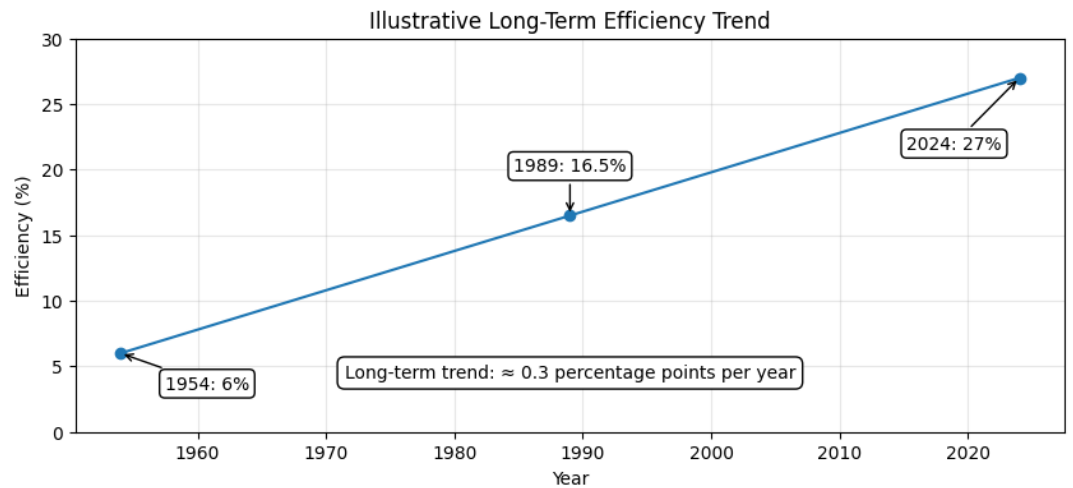


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Figure 3. Failure escalation pathway linking delamination to inverter impacts (schematic; based on [24]).

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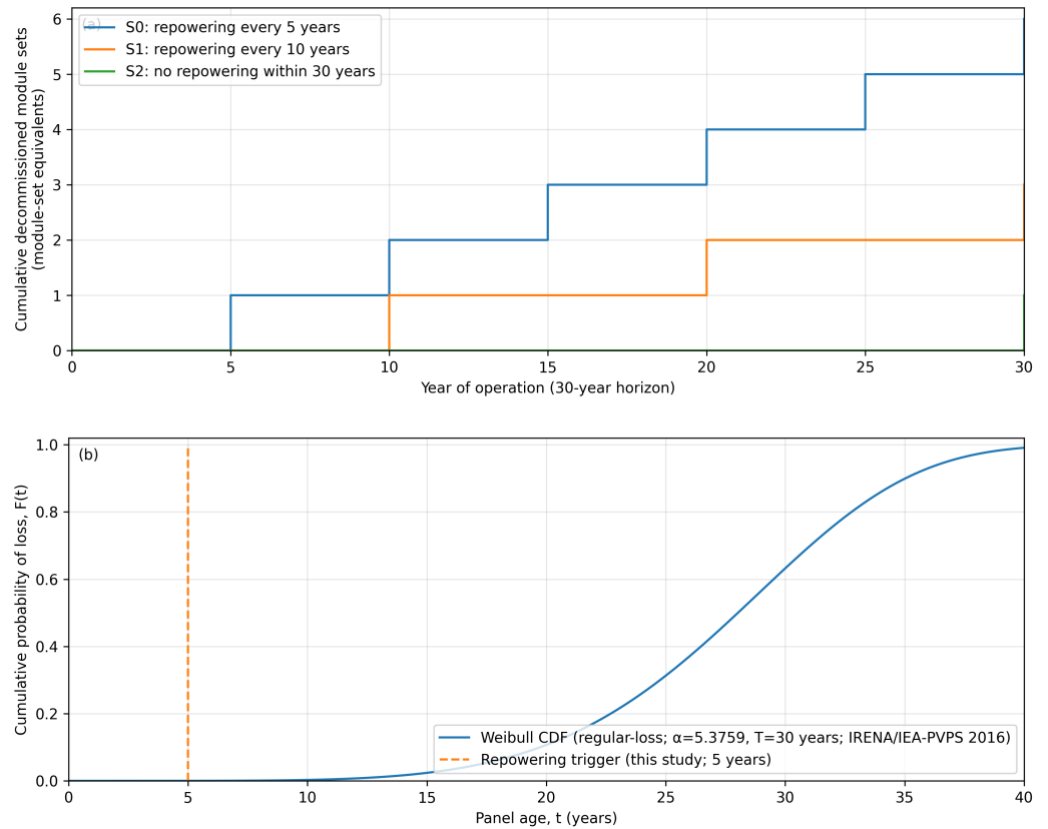


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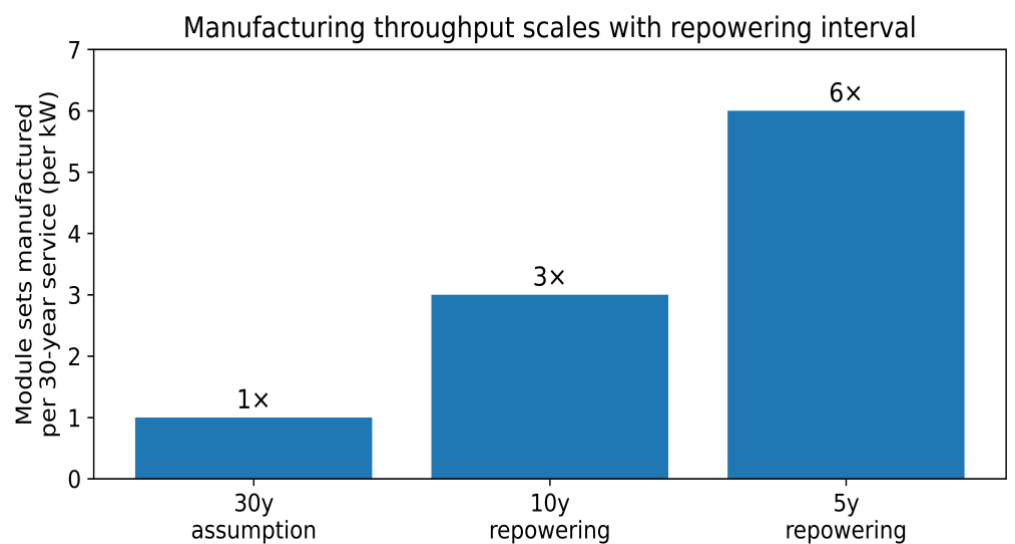
Figure 4. Illustrative long-term efficiency trend (absolute percentage points; consistent with [4]).

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501 **Figure 5.** (a) Stylised Weibull cumulative probability-of-loss curve with the repowering trigger
 502 used in S0 (5 years, dashed line). (b) Resulting cumulative waste over 30 years expressed in
 503 module-set equivalents (“step” increases at each replacement event).
 504



505 **Figure 6.** Manufacturing throughput scales with repowering interval
 506 (module sets per 30-year service).
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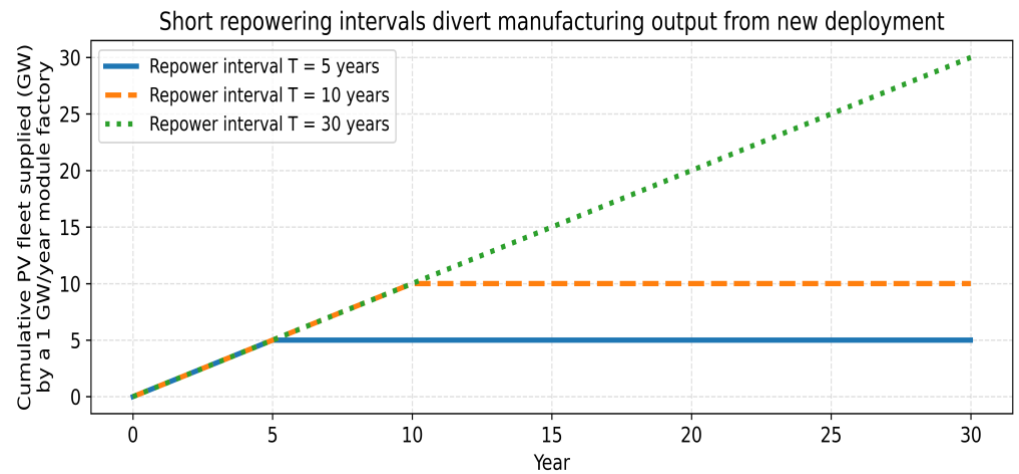


Figure 7. Short repowering intervals divert manufacturing output from new deployment (stylised illustration).

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