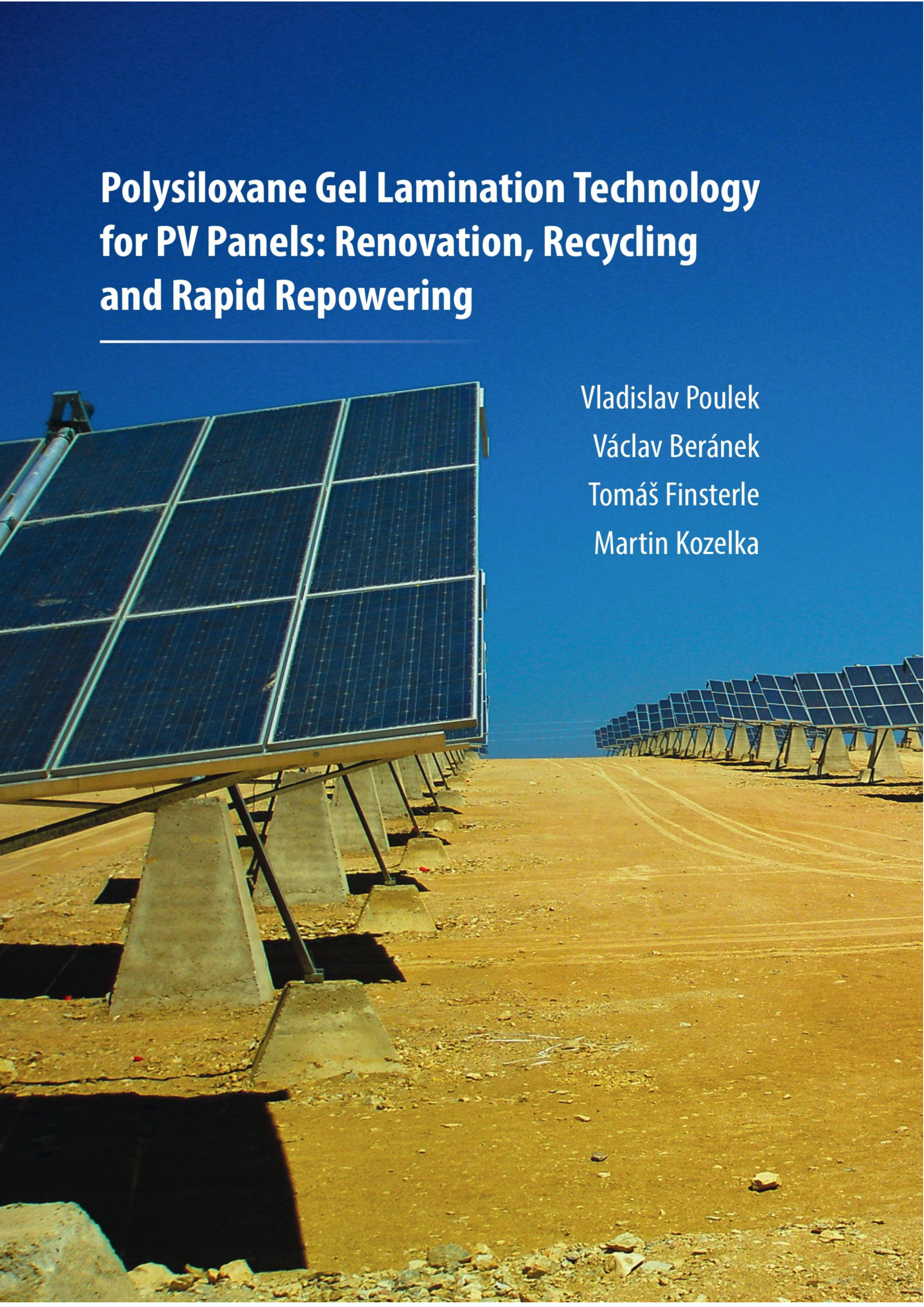

Polysiloxane Gel Lamination Technology for PV Panels: Renovation, Recycling and Rapid Repowering

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Preface

Dear readers,

This E-book is a commented collection of extended abstracts of selected scientific papers focused on photovoltaic panel reliability, PDMS gel lamination, renovation, recycling and rapid repowering.
The chapters following the introduction were originally published as independent scientific articles. In this volume, they are arranged into one coherent technological sequence. The original scientific content is preserved, while short connecting texts are added to clarify the main message of the book.
The central idea is simple: the encapsulation system of a photovoltaic module determines not only its lifetime but also its repairability, disassemblability and recyclability.
Conventional EVA or POE laminated modules are difficult to open, difficult to renovate and difficult to recycle cleanly. PDMS gel lamination offers a different module architecture based on a soft, chemically inert and optically transparent polysiloxane gel. This technology can reduce internal stress, limit corrosion mechanisms and enable much cleaner separation of module components.

This E-book follows book: **Polysiloxane Gel Lamination Technology for PV Panels: Renovation, Recycling and Rapid Repowering (**ISBN 978-80-7490-436-3)

Existing conventional panels require renovation and service life extension. New photovoltaic panels should initially be designed as repairable, disassemblable and cleanly recyclable systems.

The aim of this book is to present this technological direction clearly and practically.

June 2026 Authors

1. Introduction

This E-book is based on a collection of extended abstracts of scientific papers addressing the real field lifetime of photovoltaic panels and new technological solutions for their renovation, recycling and repowering. The papers were originally written as independent articles. In this volume, they are arranged into one continuous technical argument.

The E-book is therefore not a conventional monograph written from the beginning as one uninterrupted text. It is a commented scientific collection. Individual papers remain the core of the book. The added introduction and connecting texts explain why the papers belong together and how they support one common technological direction.

The main subject is the reliability and sustainability of photovoltaic panels in real field operation. Photovoltaic panels are often expected to operate for 25–30 years. This nominal lifetime is used in technical documentation, financial calculations and environmental assessments. However, field experience shows that the real useful lifetime of many panels can be shorter.

The reasons are practical and well known. Photovoltaic panels are exposed to humidity, rain, dew, UV radiation, thermal cycling, mechanical stress, dust, pollution and high system voltage. Over time, these stresses can cause edge delamination, water ingress, backsheet degradation, corrosion, reduced insulation resistance and inverter-related failures.

This problem is especially serious in the case of current thin-glass photovoltaic laminates.

PV laminates using 1.6/2.0 mm thin glass are currently common. Such thin glass cannot be tempered/hardened in a standard way. Therefore, it is very brittle. Therefore, in the recycling process, it will be broken.

Therefore, the vast majority of such PV laminates (glass+TPT) are crushed, and the output waste is burned. Recycling efficiency is only approximately 15% (alu. frames, plastic j-boxes).

This illustrates why the question of panel architecture is not secondary. If the laminate cannot be opened without destruction, recycling is reduced mainly to the recovery of external components, while the core laminate becomes low-value waste. A sustainable photovoltaic panel must therefore be designed not only for energy production but also for repairability, separability and clean end-of-life processing.

The problem is not only the solar cell itself. The problem is the complete panel architecture. The encapsulation system protects cells, interconnects and other internal components from the external environment. If the encapsulation fails, the whole panel becomes unreliable. If the panel is difficult to open, it is also difficult to repair, renovate or recycle cleanly.

This is why the book focuses on PDMS gel lamination. PDMS, or polydimethylsiloxane, is a soft polysiloxane gel with high optical transparency, high thermal and UV stability and very good chemical inertness. In contrast to conventional solid polymer lamination, the PDMS gel creates a panel structure that can be much more easily opened and separated.

The logic of the book is simple.

Chapter 2 presents field reliability data and shows that the real service life of first-tier photovoltaic panels can be shorter than the declared 25–30-year horizon. This chapter is based on practical reliability observations and explains why service costs and replacement needs can increase after approximately ten years of operation.

Source: *Poulek, V.; Aleš, Z.; Finsterle, T.; Libra, M.; Beránek, V.; Severová, L.; Belza, R.; Mrázek, J.; Kozelka, M.; Svoboda, R. Reliability Characteristics of First-Tier Photovoltaic Panels for Agrivoltaic Systems – Practical Consequences. Int. Agrophys.* ***2024****, 38, 383–391.*

Chapter 3 describes failure mechanisms in conventional photovoltaic panels. It focuses on the combination of edge delamination, water penetration and high-string voltage. This combination can reduce insulation resistance, cause inverter switch-off and, in serious cases, cause repeated inverter shutdowns and increase the risk of further DC-side operational failures.

Source: *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.*

Chapter 4 presents PDMS gel lamination as the core technological solution. This explains why silicone gel laminated photovoltaic panels can strongly reduce corrosion, improve long-term stability and have the potential for a much longer service life.

Source: *Poulek, V.; Strebkov, D.S.; Persic, I.S.; Libra, M. Toward 50 years lifetime of PV panels laminated with silicone gel technology. Sol. Energy 2012, 86, 3103–3108.*

Chapter 5 addresses the renovation of degraded existing photovoltaic panels. This is important because many conventional panels are already installed worldwide. They were not manufactured as disassemblable PDMS-gel panels; therefore, the main solution for them is renovation and service life extension rather than clean PDMS-gel recycling.

Source: *Poulek, V.; Tyukhov, I.; Beránek, V. On site renovation of degraded PV panels – Cost and environmental effective technology. Sol. Energy 2023, 263, 111956.*

Chapter 6 presents the clean recycling of PDMS-gel laminated photovoltaic panels. The key advantage is mechanical delamination at room temperature. This can avoid destructive shredding, high-temperature burning and aggressive chemical treatment. This technology enables very clean separation and direct reuse of valuable components.

Source: *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.*

Chapter 7 explains the importance of wet-state diagnostics. A photovoltaic panel can pass a dry insulation test and still fail under wet conditions. Rain, dew and condensation can activate leakage paths that are not visible during dry testing. Therefore, wet-state behavior is essential for realistic assessments of reliability and safety.

Source: *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.*

Chapter 8 connects the previous chapters with rapid repowering. In demanding climates, repowering after approximately five years can become technically and economically rational. This creates a serious environmental problem if the replaced panels cannot be renovated or recycled efficiently. Therefore, new panel designs must be prepared for clean disassembly and direct component reuse.

Source: *Poulek, V.; Kozelka, Rapid Five-Year Repowering of Photovoltaic Power Plants in Demanding Climates: Effective Clean Recycling and Disassemblable PDMS Gel Encapsulation to Reduce the Environmental Impact. Sustainability 2026, 18, 3599.*

A short clarification is necessary. The recycling technology described in this book is intended mainly for new PDMS-gel laminated panels. It does not directly solve the existing stock of conventional EVA or POE laminated panels already installed in the field. This existing stock must be addressed mainly by renovation.

This distinction is essential. Renovation and recycling are not competing solutions. They solve different parts of the same problem. Renovation is used mainly for existing conventional panels. Clean recycling is performed mainly for the new generation of PDMS-gel panels.

The criticism that PDMS-gel recycling does not solve old conventional panels is therefore incomplete. No new panel technology can change how old panels are manufactured. However, new technology can change the waste stream created by the rapidly growing production of new panels.

This is why timing is important. If new photovoltaic panels continue to be manufactured using difficult-to-recycle architectures, the future waste problem will increase. If new panels are designed today as repairable, disassemblable and cleanly recyclable systems, the environmental benefit can become visible within the first repowering cycles.

This benefit does not have to wait for 25–30 years. In demanding tropical climates, repowering can occur after approximately five years. In European conditions, significant repowering pressure can appear after approximately ten years. Therefore, a better panel architecture can reduce future waste much earlier than the nominal end-of-life horizon suggests.

The central message of this book is direct:

Photovoltaic sustainability is not achieved only by producing renewable electricity. It also requires reliable panels, realistic diagnostics, renovation of existing panels and a new generation of panels designed for clean recycling from the beginning.

PDMS gel lamination is presented here as a practical technological route toward this goal.

2. Field Reliability and the 10-Year Service-Life Limit

Although photovoltaic module suppliers typically declare service lifetimes of 20–30 years, field experience shows that real operating lifetimes can be substantially shorter [1,4]. Long-term monitoring of utility-scale photovoltaic power plants has indicated that even first-tier PV panels in moderate climates can fail after approximately 10–12 years of operation [1,2]. This problem becomes even more serious in agrivoltaic systems, where modules are exposed not only to standard outdoor stresses such as moisture, wind, snow, dust, UV radiation and thermal cycling but also to agricultural influences such as fertilizers, vibrations, increased humidity and soil particles [7,8]. Therefore, realistic lifetime evaluation cannot rely only on datasheet warrants or accelerated laboratory tests. It must include field reliability statistics, component degradation mechanisms and the economic consequences of failures [1,3].

2.1 Introduction

The expected long service life of PV modules is one of the central assumptions behind the economic attractiveness of photovoltaic power plants [1,4]. However, the reliability of a PV module is strongly affected by its construction: frame stiffness, glass thickness, backsheet material, encapsulant quality, edge sealing and the electrical stress imposed by the system voltage [2,8]. Over the last 25 years, the PV market has reduced module costs dramatically, but this has also been accompanied by thinner frames, thinner glass and more cost-sensitive polymer backsheets [1,6]. For example, older PV panels often use thicker glass and more robust frames, whereas recent large-area modules use thinner front glass and lower frame profiles [1]. Moreover, the DC system voltages increase from approximately 600 V to 1000–1500 V, which increases the electrical stress on the insulation systems and makes backsheet or edge-sealing defects more critical [2]. This creates a reliability paradox: insulation and encapsulation quality should improve, but in many cases, material robustness decreases [6,8].

In this chapter, the real service-life limits of PV modules under field conditions are evaluated, with special attention given to the period around the 10th to 12th years of operation. The aim is to connect material changes, failure statistics and service-cost escalation into one reliability-oriented framework [1,2].

2.2 Methodology

The reliability evaluation was based on long-term field monitoring of PV power plants using operational data from a large population of modules [1]. The dataset included 46,360 PV panels, with failures classified into degradation stages. The first stage was associated mainly with the beginning of backsheet deterioration (Fig. 1), whereas the second stage was associated with edge delamination [1,2]. Because not all panels failed during the observation period, the analysis included censored data, which is a standard practice in reliability evaluation [3].

A Weibull analysis was applied according to the reliability approach used in IEC 61649 [3]. The calculation procedure included sorting failure times, applying a modified Bernard approximation, transforming the failure probability distribution, performing linear regression and obtaining the Weibull shape and scale parameters. The main reliability indicators are the probability of failure, reliability function, probability density function, failure rate and mean operating time to failure [1,3].

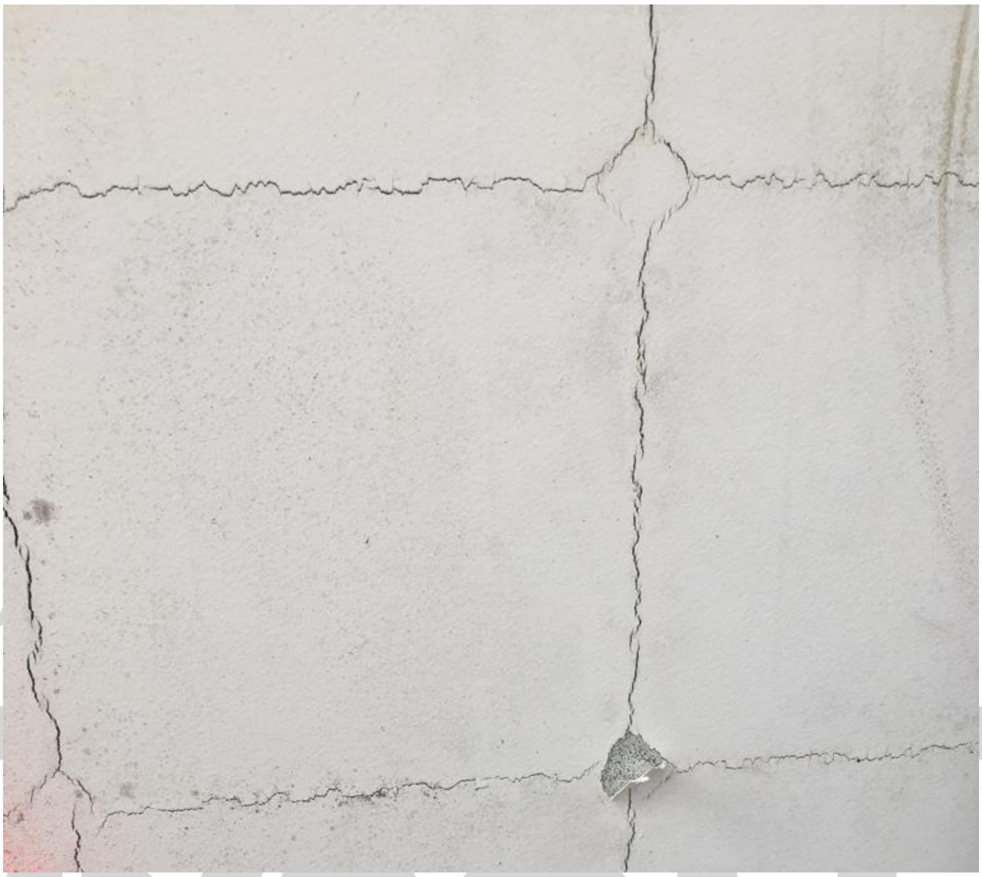

Fig. 1. *PV panel back sheet degradation*

2.3 Results and Discussion

The results show that the real onset of degradation is concentrated around the 11th year of operation [1]. The first degradation stage occurs at approximately 11.1 years (Tab. 1), and the second degradation stage occurs shortly after. This is significantly shorter than the 25–30 year lifetimes commonly reported in commercial warranties and end-of-life assumptions [1,4].

Tab 1. *Results of the mean operating time to failure (MOTTF).*

Degradation	Shape parameter a	Scale parameter b	Pearson's correlation coefficient r^2	Mean Operating Time to Failure *MOTTF*
First stage	12.788	11.559	0.6660	11.103 years
Second stage	14.131	11.800	0.6597	11.373 years

The material design changes help explain these results. The idealized frame bending depth increases sharply when the module size increases, whereas the frame stiffness does not scale accordingly. If the load-carrying frame length doubles and the load per unit length also increases, the simplified bending estimate indicates a much higher mechanical deformation risk [1]. This mechanical stress can contribute to edge defects, delamination and moisture ingress, which are among the key failure mechanisms observed in field-aged PV modules [2,8].

Backsheet degradation is another major factor. Earlier modules often use PVF-based backsheets, whereas newer designs frequently use combinations of PVDF, PET, PA or other polymers [6,8]. These materials may be less durable under long-term UV, humidity and thermal cycling, especially when polymer degradation is accelerated by local climatic conditions [8]. Because the DC system voltage has increased, the degradation of the backsheet insulation system has more severe electrical consequences than in older low-voltage arrays do [2].

The results also have direct economic consequences. Once failures begin to accelerate (Fig. 2), service costs increase rapidly [1]. Because modules are connected in strings and coupled to inverters, a single defective module can influence the output of a larger subsystem [2]. Therefore, the reliability problem is not limited to the cost of replacing a single module. It affects energy production, inverter availability, maintenance planning and the return on investment [1,4].

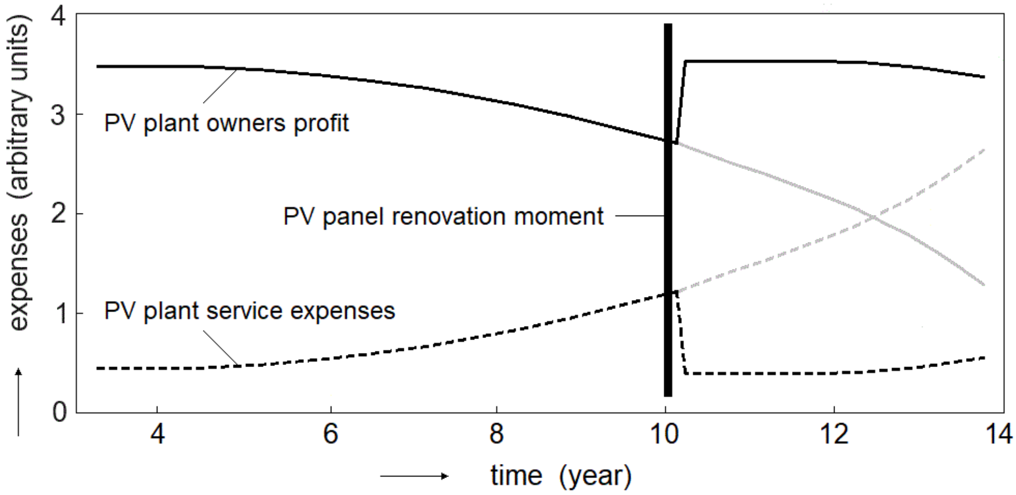

Fig. 2. Comparison between PV power plant owners' profit and service expenses.

2.4 Conclusions

Field reliability analysis has demonstrated that the effective service life limit of many PV modules can be close to 10–12 years, even when the declared warranty suggests 25–30 years [1,4]. The calculated MOTTF values of approximately 11.1 and 11.4 years show that real field degradation should be considered in financial planning, maintenance strategies and repowering decisions [1,3].

For PV plant owners, preventive diagnostics and renovation should begin before irreversible failure occurs [1,2]. For agrivoltaic systems, the reliability challenge is even stronger because agricultural environments add humidity, dust, vibrations and chemical exposure [7,8]. The next generation of PV power plants should therefore combine field-based reliability monitoring with more durable encapsulation, better edge sealing and circular end-of-life strategies [4,5].

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3. Failure Mechanisms in Conventional Modules

Conventional crystalline-silicon PV modules laminated with glass/EVA/TPT structures can exhibit several degradation mechanisms during long-term outdoor operation [1,2,4]. In moderate climates, one of the most important mechanisms is edge delamination combined with water penetration [6,7]. This failure mode is especially dangerous because it can progress from a local module defect to system-level inverter failure [4,5,6]. A conductive discharge channel can form between the internal busbars of the PV string and the grounded aluminium frame when moisture penetrates into electrically active regions [5,6,7]. This may lead to inverter switch-off, repeated protective-relay stress and, in severe cases, complete inverter destruction [4]. Therefore, delamination should not be treated as a purely cosmetic problem, but as a reliability and safety-critical degradation mechanism [4,6,7].

3.1 Introduction

The Czech Republic provides a useful field environment for studying conventional PV module degradation because a large number of systems were installed around the same period, often using similar glass/EVA/TPT module designs. Many of these plants operate in a moderate continental climate, with annual temperature and precipitation conditions that are less extreme than tropical or desert sites [3,7]. Nevertheless, field-aged PV modules can show significant degradation after long-term outdoor exposure, including delamination, moisture-related defects and insulation problems [1,2,6,7]. After approximately 9–11 years of operation, the frequency of combined PV panel and PV inverter failures increases sharply.

Manufacturers commonly specify degradation rates around 0.8% per year and guarantee performance limits over 25 years [1,2,4]. However, field observations show that defects (Figs. 1-5) such as edge delamination, moisture ingress and electrical discharge pathways can cause sudden failures that are not captured by a simple linear degradation model [4,5,6]. The objective of this chapter is to summarize the failure chain in conventional modules and to show why early diagnosis and low-cost sealing interventions can prevent larger system losses [4,8].

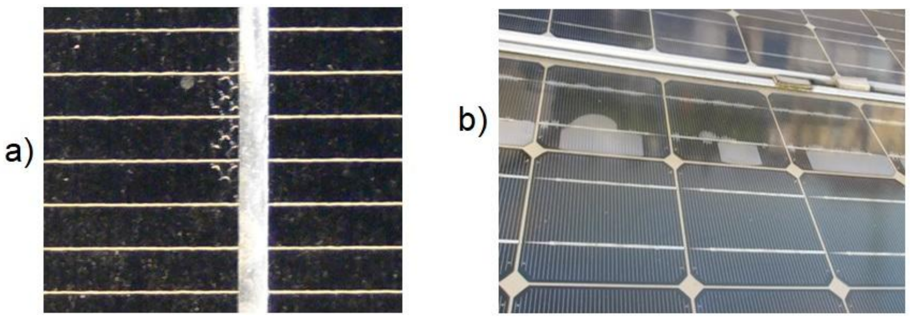

Fig. 1. *Delamination between the front cover glass and encapsulant: a) early state and b) massive delamination*

Fig. 2. *Edge delamination*

Fig. 4. *Discharge channel between string bus bar and frame*

Fig.3. *Edge delamination*

Fig. 5. *Detail of another discharge channel*

3.2 Methodology

The study is based on field observations of PV modules installed in Czech PV power plants, with detailed data from three sites in the 0.4–5 MWp range. The investigated systems used conventional framed c-Si modules connected in strings with operating voltages in the range of approximately 500–700 V DC. Failures were evaluated by visual inspection, inverter-failure records and observations of delayed morning inverter switch-on caused by low insulation resistance. Similar field-based approaches are commonly used for the assessment of aged crystalline-silicon PV modules and module reliability problems [1,2,4].

The delamination mechanisms were classified according to their location within the module stack: between the backsheet and encapsulant, between the rear encapsulant and cell, between the cell and front encapsulant and between the front encapsulant and cover glass [5,6]. Edge delamination was treated as the most critical case because it creates a path for water to reach electrically active regions near the frame [6,7]. Moisture penetration, EVA degradation products and climatic stress can further increase the risk of insulation loss and electrical leakage [5,7].

3.3 Results and Discussion

Field observations (Tab. 1) showed that no electrical breakthroughs were detected before the 9th year of operation. Around the 10th year, electric breakthroughs were detected in approximately 0.3% of PV panels, and after 11 years approximately 1% of panels were destroyed by breakthrough. Although these percentages may appear small, the system effect is much larger because one damaged panel can disconnect or damage an inverter serving many strings and many modules [4]. This confirms that PV module degradation must be assessed not only at the level of individual panels, but also at the level of strings, inverters and the whole PV power plant [4].

***Tab. 1.** Annual number of PV panel critical delamination failures at different PV power plants installed in the year 2009 in the Czech Republic*

Location	Power (MWp)	No of panels	No of panels in string	String Voltage (V)	Inverter power (kW)	No of inverters	Panel type	Number of destroyed PV inverters in the year			Number of PV panel failures in the year		
								2017	2018	2019	2017	2018	2019
Tuřany	5	18522	14	512	33	147	FT260	0	7	21 (14%)	0	12	477
Měnín	3.3	18837	13	572	7	483	ST175	12	11	20 (4%)	0	3	292
Broumov	0.4	2160	18	666	45	8	ST185	0	1	4 (50%)	0	1	13

The physical failure pathway begins with edge delamination [6]. When water penetrates the delaminated region, it can mix with ionic or acidic degradation products from EVA [5,7]. This increases conductivity and allows leakage currents to flow toward the grounded frame [5,6]. Under high DC voltage, a discharge channel may form between the internal cell interconnection and the frame. Once this occurs, the module is usually irreversibly damaged [4,6].

The second important field symptom is delayed morning inverter start-up. In wet morning conditions, modules with edge delamination can have low insulation resistance until the water evaporates [6,7]. In the monitored plants, some inverters were repeatedly delayed until approximately 10:20–10:30 in July 2020 (Tab. 2). After additional sealing of frames and backsheets with transparent polysiloxane gel, late switch-on was eliminated in the monitored cases, and the average start-up time returned to approximately 6:50–7:10. The use of silicone or polysiloxane-based encapsulation and sealing technologies has been discussed as a route toward improved long-term PV module durability [8].

Tab. 2. *Number of late switch-on inverters before and after PV panel frame sealing*

Location	Power (MWp)	No of panels in string	String Voltage (V)	Panel type	No. of late switch-on inverters	Inverters late switch-on becaue of R_{isol} below 1 MΩ			
						No. of days per month		Average switch-on time	
						Jul. 2020	Aug. 2020	Jul. 2020	Aug. 2020
Tuřany	5	14	512	FT 260-60M	15 (450kW)	31 of 31	0 of 31	10:20	7:00
Měnín	3.3	13	572	SST 175-72M	7 (70kW)	31 of 31	0 of 31	10:30	6:50
Broumov	0.4	18	666	SST 185-72M	2 (90kW)	31 of 31	0 of 31	10:30	7:10

3.4 Conclusions

Edge delamination in conventional PV modules is a critical reliability and safety issue [4,6,7]. It can lead to water penetration, reduced insulation resistance, discharge-channel formation, inverter switch-off and eventual inverter destruction [4,5,6]. The economic impact is amplified because the inverter is often more expensive than a single PV panel and because inverter downtime affects many modules simultaneously [4].

The results show that combined PV panel and inverter failures increase significantly after about 10 years of operation in moderate climates. This supports the view that 25–30 year lifetime expectations can be too optimistic for conventional EVA-laminated modules when field degradation mechanisms are considered [1,2,4,5]. Preventive sealing with polysiloxane gel can reduce the number of failures at low cost, but the most robust long-term solution is to improve encapsulation and edge durability at the module-design level [5,7,8].

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4. PDMS Gel Lamination as the Core Technological Solution

The encapsulation material is one of the most important factors determining the operational lifetime of photovoltaic modules [1,5]. Conventional EVA encapsulation is widely used because of its low cost and established production process, but it has important disadvantages: limited UV stability, possible formation of acetic acid, optical degradation and relatively high stiffness [2,5]. Silicone gel, especially polydimethylsiloxane-based gel, provides an alternative encapsulation technology with high UV stability, wide operating temperature range, excellent dielectric properties, low internal stress and reduced corrosion risk [5,6]. These properties make PDMS gel lamination a core technological solution for long-life, repairable and recyclable PV modules [3,4].

4.1 Introduction

PV module lifetime can be improved by increasing cell efficiency, reducing module cost or extending the lifetime of the encapsulation system [1]. Among these options, lifetime extension is especially important because it reduces replacement frequency, service cost and end-of-life waste [1,6]. EVA-based encapsulants have been used extensively, but their chemical composition creates limitations [2,5]. During lamination and ageing, EVA can release corrosive substances, including acetic acid [5]. These degradation products can corrode metallic contacts and contribute to delamination, insulation loss and cell interconnection failure [2,5].

Tab. 1. *Comparison of EVA and silicone gel properties (Sobolevski 1975).*

	EVA	**Silicone gel**
Long term operational temperature	(-40 , +80)°C	(-60 , +250)°C
UV radiation resistance	low	high
Operational lifetime	25 years	50 years
Laminator energy consumption per hour	49 kWh	4.5 kWh
Refractive index	1.482	1.406
Transparency for solar radiation	8% (λ=360 nm)	90% (λ=360 nm)
Transparency for solar radiation	62% (λ=400 nm)	92% (λ=400 nm)
Transparency for solar radiation	91% (λ=600÷1000 nm)	93% (λ=600÷1000 nm)
Corrosive agents - lamination	acetic acid	none
Corrosive agents - ageing	acetic acid	none
Modulus of elasticity	10.0 N/mm^2	0.006 N/mm^2
Linear coefficient of thermal expansion	4.0 x 10^{-4} K^{-1}	2.5 x 10^{-4} K^{-1}
Thermal conductivity	0.13 W/mK	0.18 W/mK

Silicone gels (Tab. 1) offer a different encapsulation concept. They are chemically neutral, highly transparent, stable under UV exposure and very soft [5,6]. Their low elastic modulus allows stress relaxation during thermal cycling, which can reduce mechanical stress on cells and interconnections [5]. Therefore, PDMS gel lamination is not only an encapsulation alternative; it is a design platform for long-lifetime PV modules [6].

4.2 Methodology

The PDMS gel system is based on a hydrosilylation reaction of low-molecular-weight polysiloxanes containing vinyl groups with hydrosiloxane crosslinking agents in the presence of a platinum catalyst. This polymer-polymer curing mechanism creates long crosslinks without releasing aggressive by-products [5]. The resulting gel combines liquid-like self-healing behavior with the dimensional stability of an elastomer.

The silicone gel encapsulation apparatus (Fig. 1) consists of a vacuum dosing and mixing unit and a vibrating stand. The system was designed for semi-automatic production with an annual capacity of approximately 1 MWp. The device uses synchronized dosing of two components, static mixing and controlled dispensing into the module. Key operating parameters include a 1:1 mixing ratio, gel consumption of approximately 1.5 kg/m² and a pouring time of approximately 5 minutes for one full module.

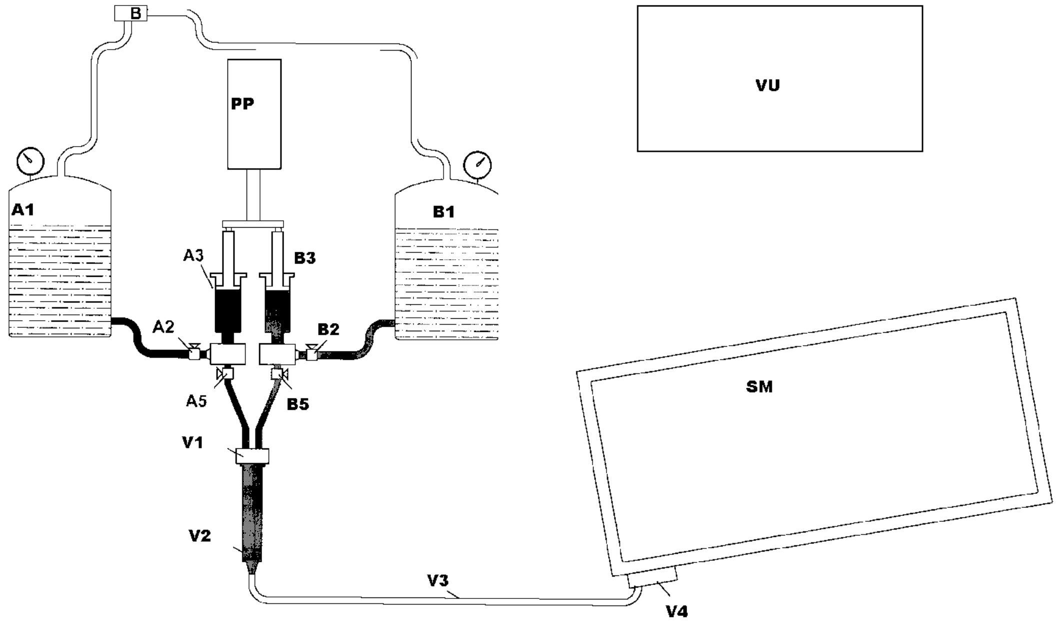

__Fig. 1.__ Scheme of the encapsulation equipment.

To evaluate material stability, glass–encapsulant–glass samples and experimental modules were exposed to accelerated UV testing and concentrated solar radiation [2]. The laboratory test used UV intensity of 140 W/m², temperature of 85 °C and duration of 1000 hours. Additional field testing was performed using a solar concentrator with approximately 3.5× concentrated radiation.

4.3 Results and Discussion

The tests showed that silicone gel retained high transparency after UV exposure. In contrast, EVA exhibited substantial transparency reduction over a broad wavelength range [2]. The difference is particularly important in the 350–700 nm range, where optical losses directly reduce module current generation [2]. Silicone gel remained substantially more transparent (Fig. 2) in the relevant solar spectrum [5].

The corrosion test produced a similarly important result. Tin-plated busbars embedded in EVA became matt and showed visible signs of corrosion (Fig. 3) after UV exposure at elevated temperature. Busbars embedded in silicone gel remained shiny and showed negligible corrosion (Fig. 4). This confirms the central technical advantage of PDMS gel encapsulation: it strongly reduces the corrosive environment inside the PV laminate [5,6].

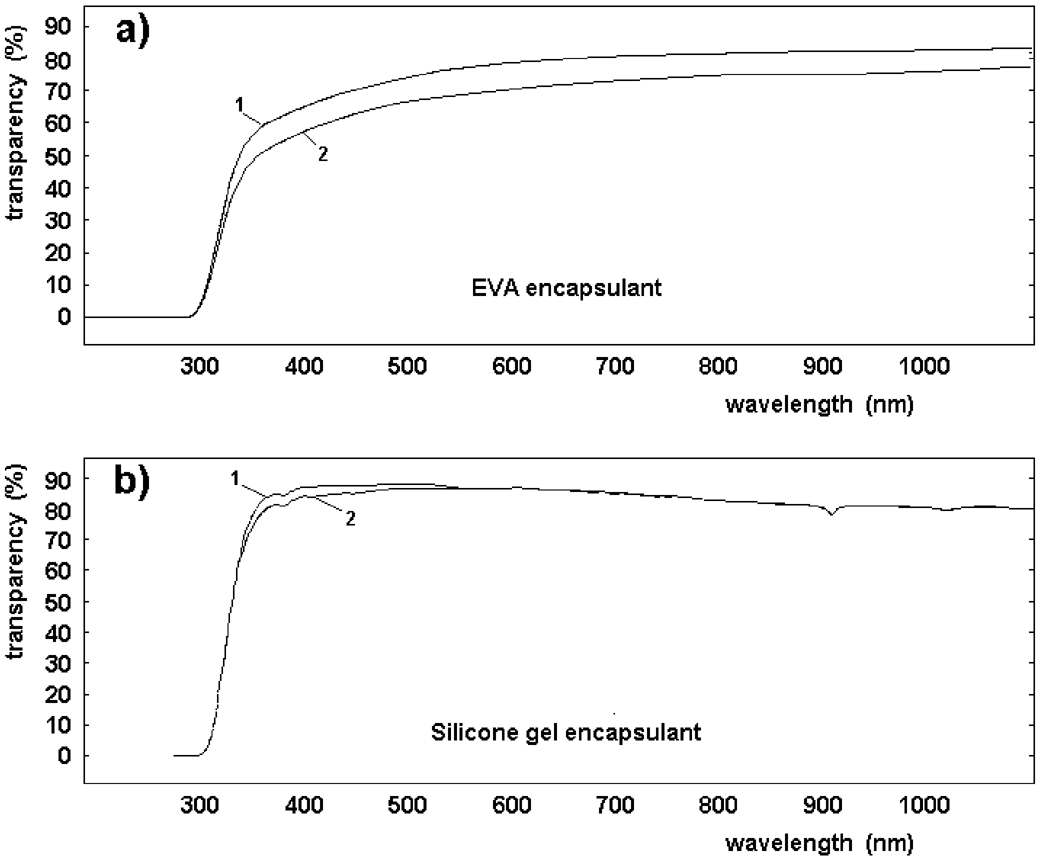

Fig. 2. a) EVA encapsulant transparency before and after UV radiation exposure, line 1 -initial, line 2 - after 1000 hours of exposure to UV radiation, b) silicone gel encapsulant transparency before and after UV radiation exposure, line 1 - initial, line 2 - after 1000 hours of exposure to UV radiation,

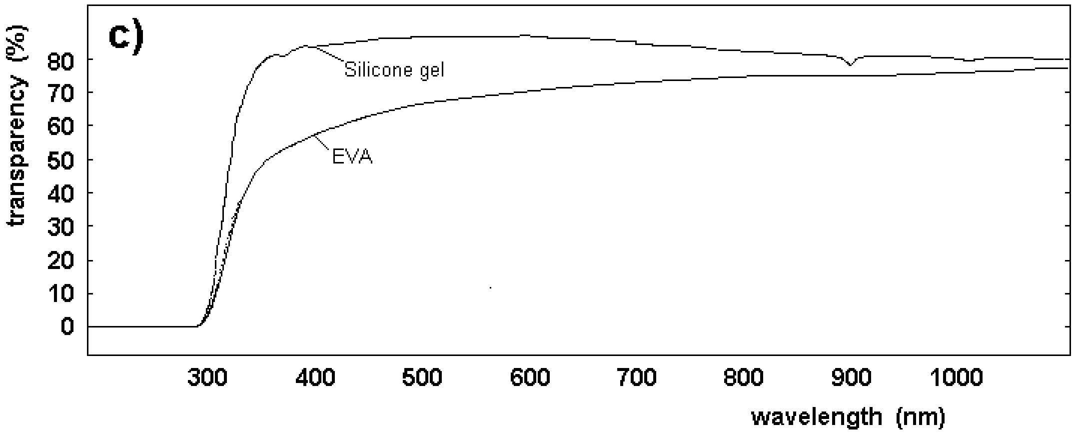

Fig. 2. *c) Transparency of EVA solid film and silicone gel after exposure to UV radiation*

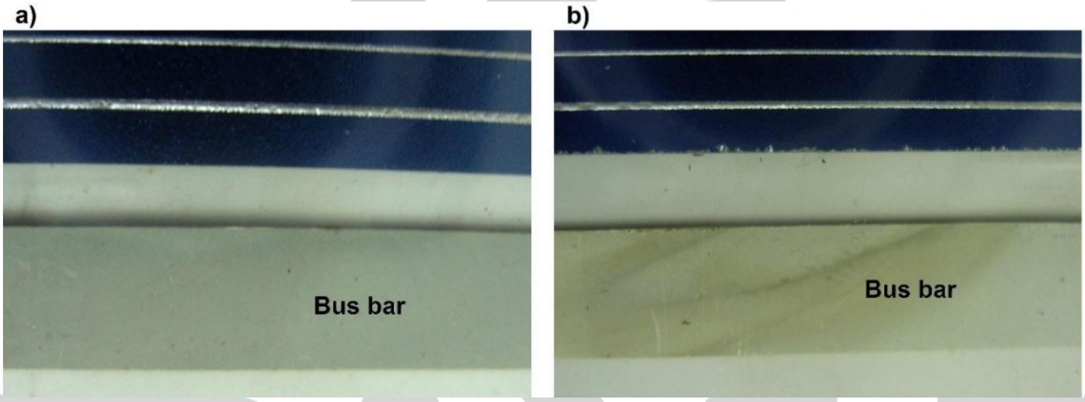

Fig. 3. *Tin plated bus bar in the EVA laminated PV panel. a) initial, b) after the test.*

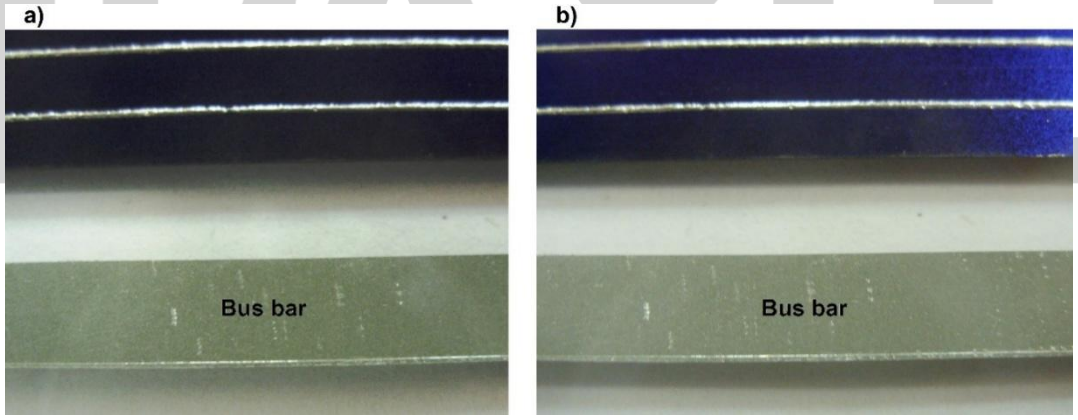

Fig. 4. *Tin plated bus bar in the silicone gel laminated PV panel. a) initial, b) after the test.*

The concentrator test also indicated stable electrical performance. Experimental gel-laminated modules tested under 3.5× solar concentration showed negligible change in key electrical parameters during the four-month test period. The combination of high UV stability, negligible corrosion and very low stiffness supports the feasibility of long-life PV modules with service lifetimes approaching 50 years [5,6].

4.4 Conclusions

PDMS gel lamination addresses several weaknesses of conventional EVA encapsulation [5]. It offers high optical stability, reduced corrosion, wide temperature tolerance and mechanical stress relaxation [5,6]. These properties can extend PV module lifetime and reduce the probability of failures caused by corrosion, delamination and interconnection damage [1,2].

The technology is also strategically important for renovation and recycling [3,4]. Because PDMS gel can be designed as a soft, demountable encapsulant, it supports circular PV module concepts in which components can be recovered or reused at end of life [3,4]. Therefore, PDMS gel lamination should be considered a core technological solution linking long lifetime, repairability and clean recycling [6].

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5. Renovation of Degraded Existing PV Panels

The encapsulation of photovoltaic (PV) panels determines the trouble-free lifetime of the panels. The quality of PV panel encapsulating components has significantly decreased over the last 25 years. Consequently, large quantities of PV panels worldwide are experiencing degradation or damage much earlier than expected.

To address this issue, an on-site renovation technology for PV panels has been developed, which involves pre-deposition diagnosis and polydimethylsiloxane (PDMS) film deposition. This technology substantially prolongs the real field lifetime of PV panels. In terms of carbon footprint, PV panel renovation is over a hundred times more effective compared to PV panel replacement. It is also a profitable solution.

5.1 Introduction

The trouble-free lifetime of PV panels is determined by their encapsulation by lamination process. However, due to intense market competition for the production of the cheapest modules, both the quantity and quality of encapsulating components have decreased over the past 25 years. For instance, 25 years ago, the front glass thickness of PV panels ranged from 4.0 to 3.2 mm. Recently, it has been decreased to 3.2-2.8mm range despite the PV panel area being four times larger. At glass/glass PV panels the usual front glass thickness was 3.2mm but it was decreased to 2.0mm or even to 1.6mm. Similarly, the height of typical PV panel frames was 40-50 mm 25 years ago, but it now ranges from 30-35 mm, despite the PV panel area being four times larger. Additionally, the use of less durable films such as PVDF (polyvinylidene fluoride), PET (polyethylene terephthalate), PA (polyamide), etc., has become common for the polymer-based backsheets, whereas it originally used the best quality polyvinyl fluoride (PVF) film. Moreover, the typical PV array system voltage has increased from about 600V DC to 900V DC, and more recently, up to 1500V DC. Therefore, the quality of insulation and encapsulation materials should be increased rather than decreased. Furthermore, many new PV plants have been installed in demanding tropical locations, leading to a decrease in ground impedance (R_{isol}) in real field conditions due to PV panel back sheet degradation.

It should be noted that laboratory simulations and accelerated testing are not equivalent to real field tests. Authoritative declarations about a 25-30 year lifetime of PV panels based on a few years of real field tests are also not relevant. Additionally, our experiments confirm that the ground impedance (R_{isol}) of PV panels in field conditions (wet and dirty) is typically reduced by more than 1000 times compared to laboratory tests of the same PV panel after cleaning and drying. Although reduced ground impedance is a major factor, it is not the only source of PV panel degradation. However, this article does not focus on describing all PV panel degradation models.

Moreover, it is important to note that PV panels are connected in series to inverters (usually 20 panels), where a failure of a single PV panel causes the disconnection of the remaining 19 panels in the string, resulting in a multiplication effect [1]. Consequently, the failure of 5% of PV panels in a PV power plant can cause a substantial reduction in energy production.

Recently, reports have been published indicating that many IEC 61215 certified PV panels, particularly those located in demanding or tropical climates, have a lifespan of less than 12 years. In some cases, this lifespan is even shorter, lasting less than 4 years, with an annual degradation rate exceeding 2% . These panels reach a total output power degradation limit of 80%, despite commercial leaflets declaring a PV panel lifetime of 25-30 years until 80% degradation. There are numerous additional reports on degradation, but they often remain unpublished due to the confidential nature of the data following early failures in PV power plants. An example of such rapid degradation occurred in an 86MW PV power plant in South Africa, where substantial output power reduction was observed just 3.5 years after the plant's opening, caused by PV panel back sheet degradation. This example aligns with the second degradation group, although exact data remain confidential [2]. Another valuable source of degradation data was measured and calculated in Qatar [3].

Even in the moderate climate of Europe [4-7], fast PV panel degradation ranging from 7 to 12 years is often associated with back sheet degradation, leading to a reduction in ground impedance (R_{isol}). International Energy Agency (IEA) report [8] evaluated possibility to replace PV panels in 10 years period. The high degradation rates result in significantly increased expenses for replacing damaged PV panels in PV power plants. As a result, some panels need to be dismantled after only 3 to 12 years, which is well before the expected lifetime of 25 to 30 years.

Therefore, servicing and maintaining new PV power plants, especially in harsh climates characterized by high temperatures and humidity, pose significant challenges. However, a new restoration method has the potential to address these issues.

5.2 PV panel renovation

The standard approach of replacing damaged PV panels with new ones is expensive and also not environmentally friendly in terms of carbon footprint. Several technologies for onsite PV panel renovation have been tested [1]. Some of these technologies utilize a thin polydimethylsiloxane (PDMS) film, approximately 0.1 mm in thickness, as depicted in our Fig 1. PDMS is a hydrophobic material known for its excellent thermal stability, with a thermal resistance of 250°C and a Relative Thermal Index (RTI) of 150°C. It also exhibits good resistance to ultraviolet radiation. Interestingly, PDMS is the same material used in high-temperature, long-lasting PV panel lamination technology [9].

***Fig. 1** Picture of renovation PDMS film on back side of PV panel.*

We have developed a new PV panel renovation process that includes not only on-site thin 0.1 mm PDMS film deposition technology but also a comprehensive on-site PV panel diagnosis, including measurements of ground impedance (R_{isol}), delamination, and other factors, both before and after the protective film deposition. The two component PDMS has been deposited on site by spraying method. Fast cure (30 minutes at temperature 25 degrees Celsius) PDMS was used. The film thickness was measured by micrometer gauge. The main method to check the renovation film quality has been regular testing of ground impedance (R_{isol}) in real field (wet) conditions. To double check the renovation quality early morning inverter switch on time was monitored. Once there are troubles with low R_{isol} the inverters are switched on several hours later as the inverters have internal R_{isol} safety control [1]. Besides R_{isol} tests visual check of chalking and edge delamination was performed.

To evaluate the effectiveness of our renovation process, we selected two test sets comprising 40 first-tier (bankable) PV panels rated at 250W each. These panels were installed at a 2 MW PV power plant situated in a moderate climate region of central Europe. The first set consisted of damaged PV panels that were repaired using a 0.1 mm thin PDMS film with fast curing properties. The repaired panels were observed for a period of 5 years. As shown in Fig 2, the real-field (wet) PV panel ground impedance (R_{isol}) was successfully restored after the renovation and remained nearly unchanged throughout the 5-year observation period.

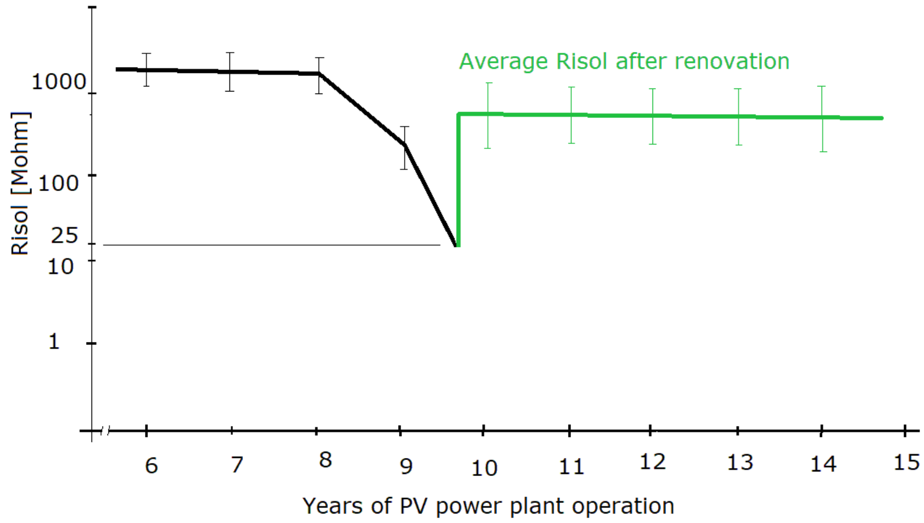

Fig.2. *Real field (wet) Risol of PV panels before and after PV panel renovation.*

The tests demonstrate that the lifetime of repaired PV panels could be extended by 5 years or even more. The low cost renovation can be performed repeatedly in 5-7 years period. In contrast, the second set of PV panels without renovation experienced significant degradation after 5 years, leading to non-repairable failure. This failure was characterized by the presence of electric discharge channels between the PV panel's internal busbars and the grounded PV panel frame, with R_{isol} values falling below the critical threshold of 25 Mohm. At the beginning of the test (10 years of operation) R_{isol} of 18 panels was below 25 Mohm. At the end of the test (15 years of operation) R_{isol} of all 40 PV panels was well below 25 Mohm. Furthermore, delamination of the panel edges occurred, allowing water penetration and degradation of the back surface laminate, resulting in cracks and chalking. It is crucial to conduct PV panel renovation within approximately one year after a rapid decrease in R_{isol} is observed. Once an electric discharge channel is formed, the PV panel becomes irreparable. To date, a total of 41 MW of PV panels have been successfully repaired using the thin siloxane film method.

5.3 Conclusions

A brief review of publications on the reliability of photovoltaic modules reveals that the modules' service life is often shorter than the manufacturer's warranty. One of the factors contributing to the reduced service life of solar modules is the quality of materials used on the back side of the modules.

The proposed technology for on-site upgrading of solar PV modules is approximately 11 times more cost-effective than replacing the entire modules and about 120 times more effective in terms of carbon footprint reduction. The PDMS coating is stable for more than 5 years of exposure in and allowed to restore the electrical insulation properties of the modules. Therefore, for PV power plant owners (end users), renovating PV panels proves to be a profitable and environmentally sound solution.

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6. Clean Recycling of PDMS-Gel Laminated PV Panels

Photovoltaic waste is becoming a major sustainability challenge as global PV deployment increases and older modules reach the end of life [1,3,4,8]. Conventional EVA/POE-laminated panels are difficult to recycle because the encapsulant strongly binds the module stack [1,4,8]. Standard recycling often requires high-temperature treatment, chemical processing or mechanical crushing [1,4]. These methods consume energy and may generate hazardous residues or low-value contaminated material streams [1,3,4]. PV panels laminated with very soft PDMS gels offer an alternative route: clean mechanical delamination at room temperature, direct reuse of glass sheets and high recycling efficiency without burning or aggressive chemical etching [2,5,6].

6.1 Introduction

Most conventional PV modules are laminated with EVA or POE encapsulants [1,4,8]. These polymers are effective during manufacturing, but at the end of life, they make the separation of glass, cells, metals and polymer layers difficult [1,4]. In practice, the front glass is often crushed, and the resulting glass grit can be contaminated with silicon cell fragments and metallic conductors [1,4]. Although theoretical recycling efficiency can be high, real recycling outcomes are often limited by contamination, processing costs and the difficulty of clean laminate separation [1,3,4,8].

PDMS-gel laminated modules are designed differently. The very soft gel allows the glass/glass laminate to be mechanically opened at room temperature [5,6]. This makes it possible to recover large intact glass sheets and collect PDMS gel clusters separately [2,5]. Because the process avoids high-temperature burning and aggressive etching, it significantly reduces hazardous emissions and improves the circular economy value of PV module end-of-life processing [1,2,4].

6.2. Methodology

PV panels laminated with soft PDMS gels were manufactured using previously developed silicone gel lamination technology [5,6]. The recycling tests focused on bifacial glass/glass PV panels. A preliminary fast delamination test was performed, but excessive mechanical loading fractured the upper glass sheet. The optimized manual process was then applied to seven identical modules. Among the 16 glass sheets, 15 were successfully separated, corresponding to a glass separation efficiency of 93.75%.

The room-temperature disassembly sequence (Figs 1- 4) consisted of five steps: manual removal of the aluminum frame, manual removal of the polymer junction box, slow insertion of HDPE wedges between the front and rear glass sheets, manual separation of the glass sheets and vacuum collection of soft PDMS gel clusters. The manual disassembly time was approximately 22 minutes, whereas an automated line is expected to reduce the process time to approximately 15 minutes. This method follows the principle that clean mechanical separation can improve recycling quality by reducing mixed and contaminated material streams [1,2,4].

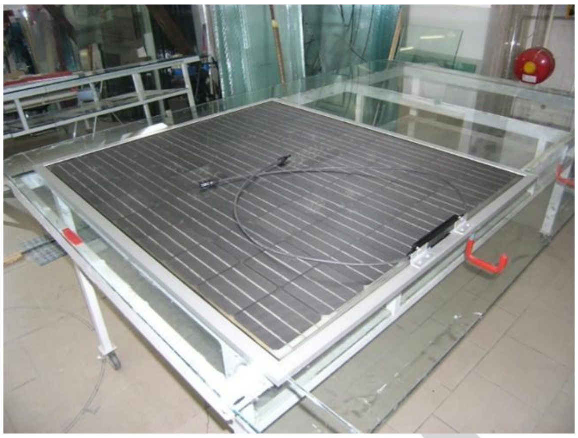

Fig. 1. *Bifacial glass/glass PV panels laminated with PDMS gels on the working bench.*

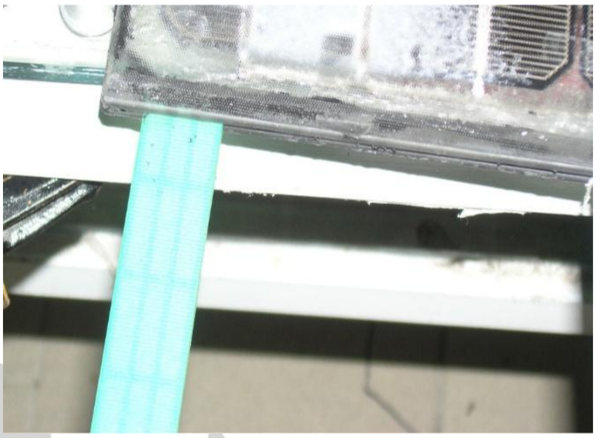

Fig. 2. *A high-density polyethylene (HDPE) wedge is pushed in between the glass sheets.*

Fig. 3. *Separation of non-damaged glass sheets with the remaining siloxane gel clusters.*

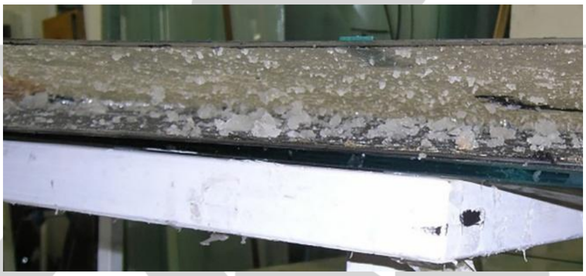

Fig. 4. *Soft siloxane clusters can be easily collected and recycled into silicone rubber*

6.3 Results and Discussion

The key difference between conventional EVA/POE modules and PDMS-gel modules appears during glass recovery [1,2,4]. In conventional recycling, glass is typically crushed and may require remelting [1,4]. With respect to the PDMS modules, both glass sheets can be recovered intact (Figs. 1- 4) and directly reused (Tab. 1), for example, in greenhouses, industrial glazing or as rear glass for new glass/glass PV panels after additional cleaning [2,5]. Avoiding glass remelting is important because glass melting requires a large amount of energy and therefore contributes to the environmental burden of recycling [2,9].

Tab 1. *Possible recycling methods for PV panel components—dangerous waste direct emissions. PV panel area: 2 square meters.*

	EVA/POE Laminated Glass/TPT PV Panel, Weight ~24 kg	**PDMS Laminated Glass/Glass PV Panel, Weight ~37 kg**
Front glass sheet [15 kg]	Glass crushing and remelting [15 kg glass grit emissions]	Glass sheet direct reuse [15 kg] No emissions
Backsheet	Polymer/TPT film burning [+2 kg burning gas emissions]	Glass sheet direct reuse [15 kg] No emissions
Encapsulant [3 kg]	EVA/POE etching (or burning) [+3 kg etching emissions—acids]	PDMS e-beam polymerization No etching and no emissions
Polymer J-box [~0.5 kg]	Remelting No emissions	Remelting No emissions
Aluminum frame [2 kg]	Remelting No emissions	Remelting No emissions
c-Si solar cells [0.8 kg]	Remelting metallurgical-grade silicon No emissions	Remelting metallurgical-grade silicon No emissions
Direct Reuse	0 kg	30 kg (81% weight)
Direct Emissions	+20 kg (83% weight)	0 kg
Recycling Efficiency	~15% up to 90%	~95% up to 98%

6.4 Conclusions

PV panel lamination/encapsulation technology using very soft polydimethylsiloxane (PDMS) gels is very effective for achieving both beginning-of-life (BOL) low degradation rates and end-of-life (EOL) recycling. Compared with existing PV panels, PV panels laminated with very soft PDMS gels are much more effective throughout their whole life cycle, from BOL to EOL.

The main advantages of the new recycling process are as follows:

- Environmentally sustainable—a recycling efficiency of 95–98% (usual recycling efficiency: ~15–90%, Table 2).
- Very simple mechanical delamination/disassembly at room temperature.
- Very clean—negatively dangerous waste emissions (no burning or chemical etching; Table 1).
- The direct reuse of PV panel components exceeds +80% (usually no component reuse; Table 1).
- Energy consumption is reduced by more than two times (compared with usual recycling).
- Low cost—more than two times less recycling expense (than usual recycling).

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7. Wet-State Diagnostics and the 5–10 Year Reality

Ground impedance, or insulation resistance, is one of the most important safety and reliability indicators for PV modules [1,3,4]. In routine field practice, it is often measured under dry conditions because dry testing is fast and simple [3,7]. However, PV modules frequently operate under wet conditions caused by dew, fog, rain or condensation, especially around sunrise [2,5]. Under these conditions, leakage pathways can become active and insulation resistance can drop by orders of magnitude [2,3,5,7]. This chapter demonstrates that dry-only testing can miss critical wet-state failures and that wet-state diagnostics should become part of repowering, revamping and end-of-life decision-making [1,7,9].

7.1 Introduction

PV modules must maintain sufficient electrical insulation between active DC circuits and accessible conductive parts such as aluminium frames [1,3,4]. If insulation resistance becomes too low, ground-fault protection can trigger inverter trips, and leakage currents can become a safety hazard [3,4,8]. IEC 61215 includes the MQT 15 wet leakage current test, where modules are tested in a conductive wet environment [1]. For modules larger than 0.1 m², the criterion is usually expressed as [1]:

Equation (1):

$$R_{\text{wet}} \times A \geq 40\ \text{M}\Omega \cdot \text{m}^2 \tag{1}$$

where R_{wet} is the measured wet insulation resistance and A is the module area [1].

Although this test is important for type approval, it is less commonly applied to field-aged modules [1,7]. This creates a diagnostic gap: modules that pass dry testing may fail under wet operating conditions [5,7]. Such dry-pass/wet-fail modules are especially important for PV fleets approaching 5–10 years of operation, where repowering decisions are often being considered [7,9,10].

7.2 Methodology

The study evaluated 37 field-aged crystalline-silicon PV modules from utility-scale plants operating in a moderate Central European climate [7]. Dry insulation resistance was measured at 1000 V DC with a 2-minute dwell time [1,7]. The wet insulation resistance was measured (Figs. 1,2) according to IEC 61215 MQT 15 using a saltwater bath with solution resistivity below 3500 Ω·cm [1]. The module leads were short-circuited and connected to the positive terminal of the insulation tester, while the bath electrode was connected to the negative terminal [1,7]. After the 2-minute dwell, R_{wet} was recorded [1,7].

For representative module areas of 1.6, 1.8 and 2.0 m², the IEC wet-resistance limits are 25.0, 22.2 and 20.0 MΩ respectively [1]. The analysis also calculated the dry-to-wet ratio [7]:

Equation (2):

$$R_{\text{ratio}} = \frac{R_{\text{dry}}}{R_{\text{wet}}}, \tag{2}$$

Modules with R_{wet} approximately equal to 0 Ω were treated as catastrophic wet failures [7].

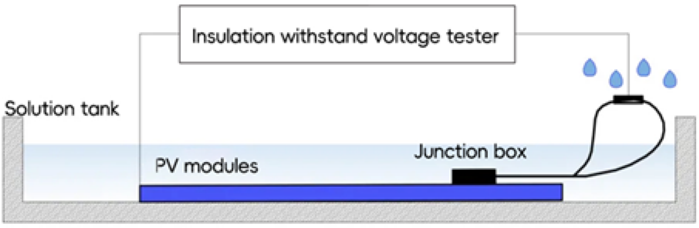

***Fig 1**. Schematic diagram of the measurement circuit (adapted from Firman et al, 2022)*

***Fig 2.** Photograph of the actual laboratory installation with the PP tank, immersed module and insulation tester.*

7.3 Results and Discussion

The results (Tab. 1, 2) show a strong difference between dry and wet insulation resistance [7]. The median dry resistance was 42.4 GΩ, while the median wet resistance (Fig. 3) was 462.5 MΩ [7]. Therefore, the dry measurement overestimated the wet resistance by approximately 110× at the median [7]. The dry-to-wet ratio was strongly skewed, with several modules showing drops of more than two orders of magnitude [5,7].

Tab. 1. *Summary statistics for dry and IEC-wet insulation resistance and dry-to-wet ratio (N = 37).*

Metric	Rdry	Rwet	Ratio Rdry/Rwet
Median	42.4 GΩ	462.5 MΩ	109.7×
Mean	(not used; skewed)	(not used; skewed)	543.5×
Minimum (non-zero)	3.27 MΩ (Panel 14)	4.38 MΩ (Panel 34)	0.07× (Panel 33)
Maximum	110.4 GΩ (Panel 15)	5.99 GΩ (Panel 7)	856.6× (Panel 12)

Tab. 2. *Compliance of the 37 field-aged modules with the IEC 40 MΩ·m2 insulation-resistance criterion for typical module areas.*

Assumed Area A [m2]	Wet Limit R_{limit} = 40/A [MΩ]	IEC Wet Pass [Count]	IEC Wet Fail [Count]	Dry Fail [Count]	Dry-Pass/Wet-Fail [Count]
1.6	25.0	29	8	4	5
1.8	22.2	29	8	3	5
2.0	20.0	29	8	3	5

The most important operational finding is the existence of dry-pass/wet-fail modules [7]. In the dataset, three modules failed the criterion already in the dry state, but eight failed under IEC-wet conditions [7]. Five modules passed dry screening but failed wet testing [7]. In a large PV plant, such a fraction could translate into hundreds of modules that appear safe during dry inspection but can trigger inverter trips or leakage alarms under dew or rain [2,7,8].

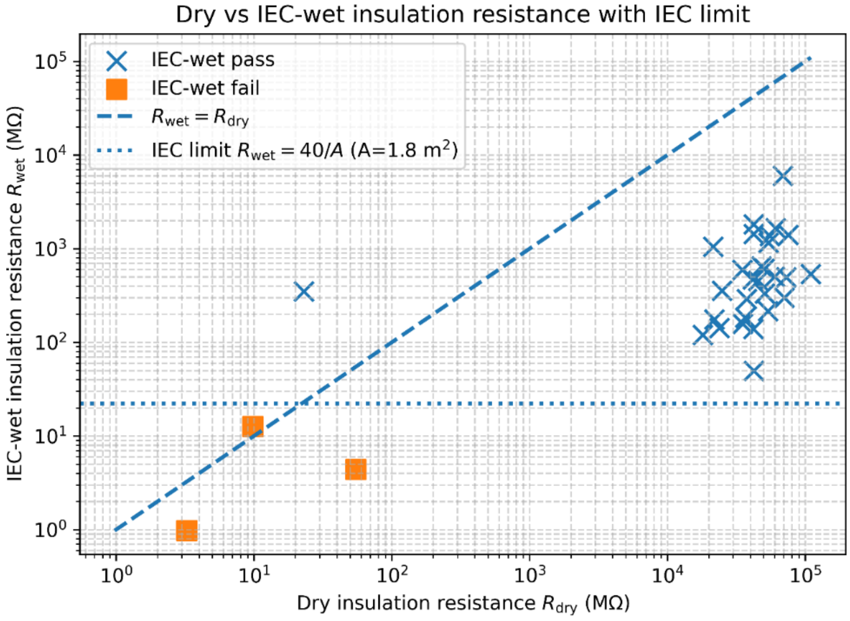

Fig. 3. *Scatter plot of dry insulation resistance Rdry versus IEC-wet resistance R_{wet} (log-log).*

The physical explanation is linked to wet leakage pathways [2,3,5]. Dew and rain films reduce surface resistance and can activate leakage paths along the glass surface, module edges, backsheets, junction boxes and frame interfaces [2,5,6]. The sunrise period is especially critical because surface wetness is high while module temperature is low, which increases open-circuit voltage [2,8]. This combination can make ground-fault events more likely in the early morning [2,3,8].

The proposed dry threshold of approximately 55.5 GΩ for a representative area of 1.8 m^2 is not intended as a pass/fail limit [7]. It should be used as a conservative triage indicator: modules below this value should be prioritized for IEC-wet testing and closer inspection [1,7].

7.4 Conclusions

Dry-only insulation testing is not sufficient to evaluate the safety of field-aged PV modules [5,7]. Wet-state testing can reveal latent insulation failures that are not visible in dry measurements [1,7]. The median dry-to-wet drop of approximately 110× and the occurrence of five dry-pass/wet-fail modules in a sample of 37 show that wet diagnostics should be integrated into PV fleet management [7,10].

For repowering and revamping decisions within 5–10 years, wet insulation resistance provides an important selection criterion [7,9,10]. Modules that pass both dry and wet tests may remain in service, while wet-failing modules should be removed, replaced or directed to suitable recycling routes [7,9]. This links electrical safety, asset management and circular-economy strategy [7,9,10].

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8. Rapid Five-Year Repowering and Environmental Impact

The economic logic of PV repowering is influenced by two forces. The first is reliability: wet insulation failures, delayed morning inverter start-up, edge delamination and discharge-channel formation can reduce availability and increase operational risk [6,7,8,9]. The second is technological improvement: newer modules often provide higher power density and efficiency, making replacement attractive when land areas and grid connections are already available [1,2,4].

In demanding climates, these forces (Fig. 1) can combine [6,7,8,9]. A plant may not reach the nominal 25–30 year service life before replacement becomes the preferred operational decision [1,6]. From a sustainability perspective, the consequence is mechanical: shorter repowering intervals multiply module production, transport, installation and end-of-life flows [2,3,10]. The goal of this chapter is to quantify this scaling effect and to show why disassemblable PDMS-gel module designs can reduce the environmental burden of rapid repowering [3,10].

8.1 Introduction

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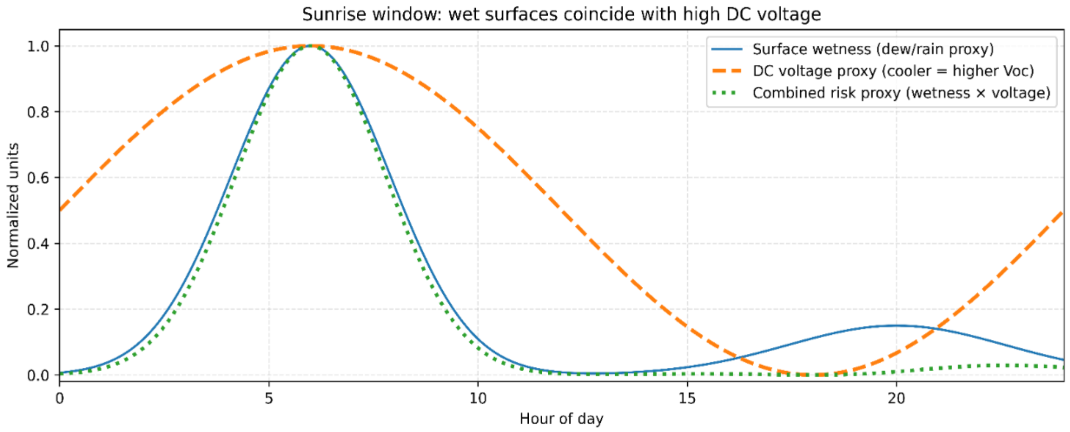

Fig. 1. Sunrise window: wet surfaces coincide with high DC voltage (stylized proxy, supported by [15–17]).

8.2 Methodology

The analysis uses a scenario-based 30-year planning horizon with a functional unit of 1 kW installed module capacity [1,2,3]. The model focuses on module replacement because modules dominate the repeated mass flow during repowering [2,3,10]. Balance-of-system components are assumed to be largely reused, although their impacts should be included in future detailed studies [1,3].

Three scenarios (Tab. 1) are defined. Scenario S0 represents rapid repowering every five years. Scenario S1 represents repowering every ten years. Scenario S2 represents the baseline expectation of no module replacement within 30 years [1,2,3].

Tab. 1. *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 main indicator is the module throughput multiplier [2,3]:

$$M = \frac{H}{R} \tag{1}$$

where H is the planning horizon and R is the repowering interval. With H = **30 years**, a five-year interval gives M = **6**, a ten-year interval gives M = **3** and a thirty-year interval gives M = **1**. Additional indicators include waste timing, repeated end-of-life surges and manufacturing diversion from new deployment to replacement demand [2,3,10].

8.3 Results and Discussion

The results show a large discontinuity between the nominal 30-year expectation and the five-year repowering case [1,2,6]. Under S2, one module set is installed and decommissioned at the end of the 30-year horizon. Under S0, full replacement occurs at years 5, 10, 15, 20 and 25, followed by final decommissioning at year 30 [2,3]. This creates repeated waste surges (Fig. 2) rather than a single end-of-life event [3,10].

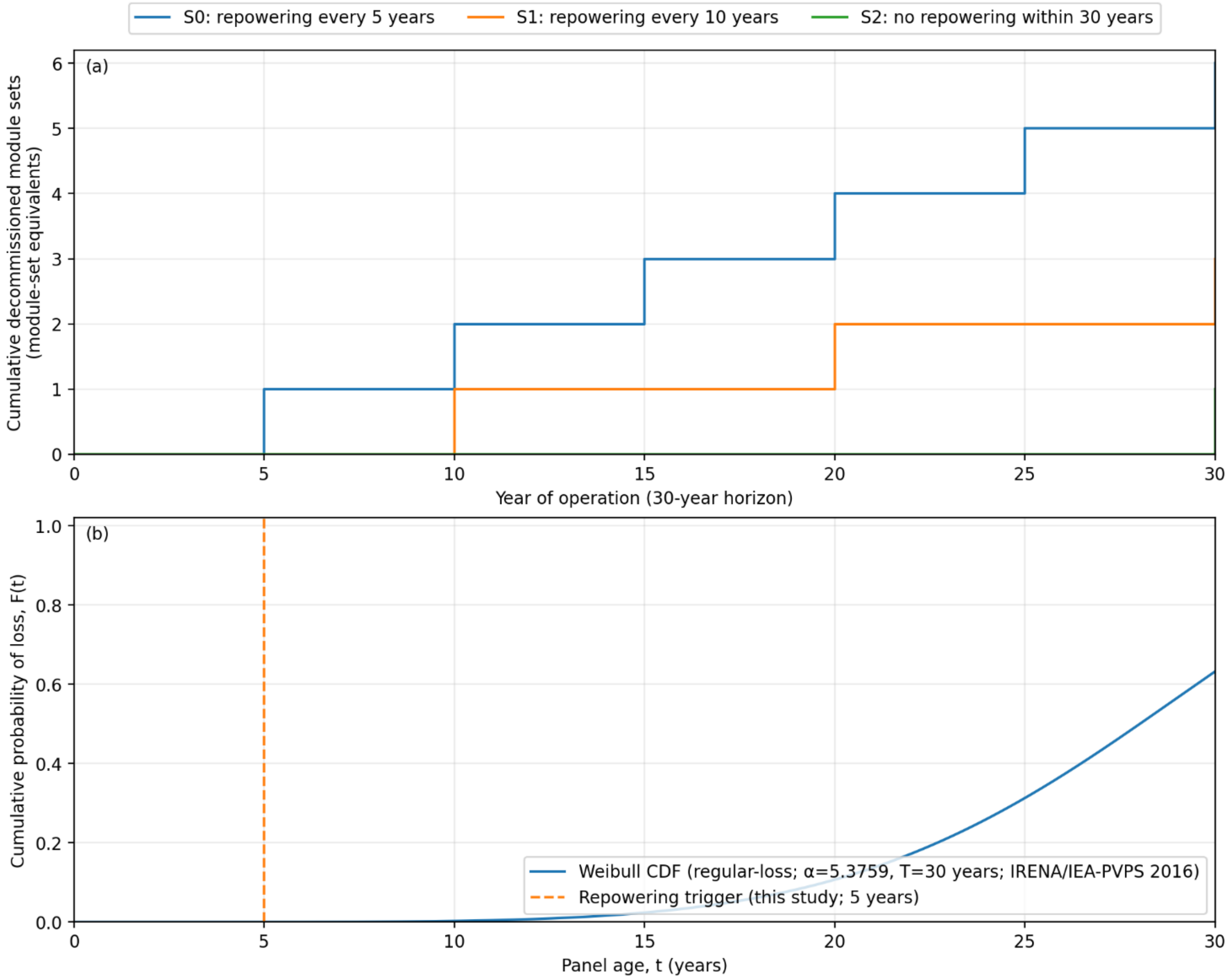

Fig. 2. *(**a**) Weibull-based reference curve with the repowering trigger used in S0 (5 years, dashed line). (**b**) Stylized cumulative waste over 30 years expressed in module-set equivalents, with step increases occurring during replacement event years [29].*

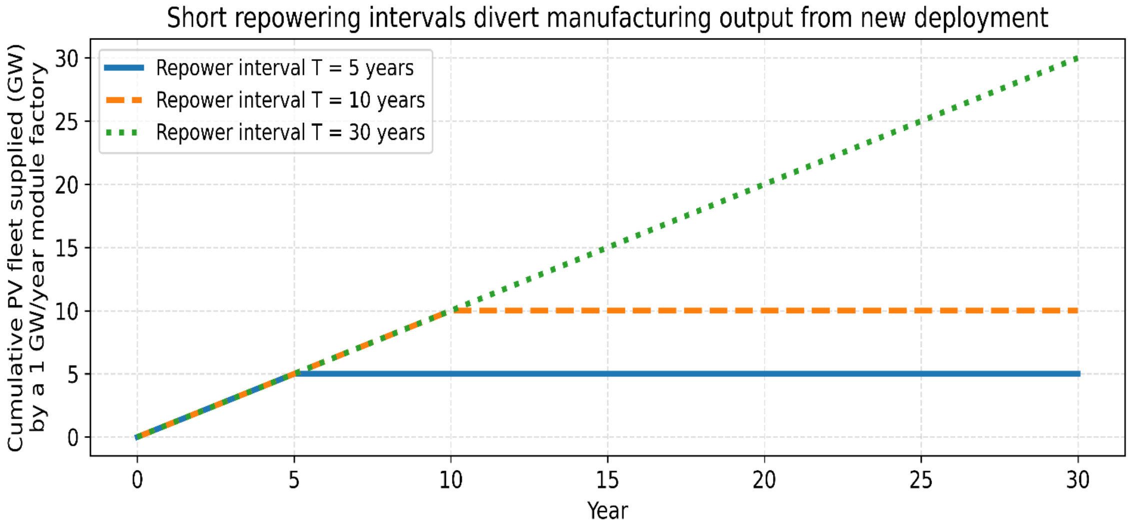

Fig. 3. *Short repowering intervals divert manufacturing output from new deployment (stylized illustration).*

The multiplier is the core sustainability result. A five-year interval requires six complete module sets over 30 years [2,3]. This means that the manufacturing, transport and recycling flows are repeated six times. The exact life-cycle inventory values may vary by technology and location, but the first-order scaling effect is governed by the replacement interval itself [1,2,3].

Rapid repowering also creates a manufacturing capacity constraint [2,4]. If factory output is increasingly consumed by replacement modules, less capacity remains (Fig. 3) for new PV deployment [2]. In a simplified example, a factory producing 1 GW/year can supply 5 GW of new capacity during the first five years, but if the installed fleet must then be replaced every five years, future output may be absorbed by replacement demand [2,4]. Therefore, rapid renewal affects not only waste management but also the speed of net PV expansion [2,3,4].

The mitigation strategy is to make repowering cleaner [3,10]. Soft PDMS-gel laminated modules can be designed for room-temperature mechanical delamination, direct reuse of glass and high recycling efficiency [10]. This does not eliminate the need for repowering, but it reduces the environmental burden when replacement becomes unavoidable [3,10]. The technical objective is therefore not only to recycle more but also to design modules so that repowering becomes a low-emission, high-reuse operation [3,10].

8.4 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 polydimethylsiloxane (PDMS) gel encapsulation—that allows room-temperature delamination, high-efficiency recycling, and high direct reuse [10]. 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 reality for a subset of plants.
2. Aggressive/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.
4. 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) [10] and (ii) risk-based wet condition insulation verification to reduce latent wet failures and operational escalation.

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Polysiloxane Gel Lamination Technology for PV Panels: Renovation, Recycling and Rapid Repowering

Reviewed by: Prof. Dr. Monika Božíková, June 2026

Why Polysiloxane Gel Lamination?

This book presents a coherent sequence of published scientific papers on PV panel reliability, renovation, clean recycling and rapid repowering. Polysiloxane gel lamination enables a repairable, disassemblable and environmentally sustainable PV module architecture.

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